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DEVELOPMENT OF A METHOD FOR UPGRADING PARTICULATE COAL

By

B.Y.H. Wong*

R.J. Germain**

M.J. Kramer**

D. Avery**

A. Ayoub**

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Canada Centre for Mineral and Energy Technology,
Energy, Mines and Resources Canada

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1. SUMMARY

This cost-shared research program between Gulf and CANMET has provided an important data base for the development of the Gulf Beneficiation Process. The simple operational feature of this process was demonstrated at a major Canadian coal operation at feed rates up to 150 tonnes/hr in 1986. The technical feasibility of the single-stage process has been established and continuing research has led to the development of a two-stage operation, which has the additional benefit of more effective utilization of petroleum residuum. The application of residuum through the use of emulsion also offers greater flexibility in process operation.

The results of this research contract show that at optimum processing conditions, upgraded products of marginal thermal coals produced by the Gulf Beneficiation Process are expected to meet specifications for thermal coals destined for the export markets. There is substantial benefit to enhancing the calorific value of marginal thermal coals above the 6,000 kcal/kg value. This level of heating value not only opens up new markets, but is also psychologically important in coal marketing. In addition to heating value enhancement, the elimination of the dusting problem is also beneficial for coal marketing. Drying coals to below their equilibrium moisture level is an ambitious attempt and yet necessary for thermal coals with marginal calorific value. If the stability of the upgraded products can be improved to levels superior to their feedstocks, there is a great potential for the Gulf Process to make a significant impact on upgrading low rank coals.

A number of process variables are studied in this research program. It was found from the results that processing temperature has the largest effect on equilibrium moisture reduction. The major effect of residuum level is on product stability. Residuum type shows only a minor effect on equilibrium moisture reduction. The effect of residence time is minimal. The optimum conditions used for a typical high volatile bituminous coal are 300°C in processing temperature, 4 wt% of residuum application, and 12 minutes residence time. For coals of ranks lower than bituminous, higher residuum levels will be more suitable because of their high equilibrium moistures.

There are two basic options in the process sequence: a single-stage where drying and residuum application take place in one drum dryer, or a two-stage operation where coal drying and residuum application are carried out in separate process units. The two-stage operation is the preferred route as this mode of operation will more effectively utilize petroleum residuum which is the main cost component in the Gulf Process. Residuum can be applied in its neat form or as an emulsion. The use of emulsion offers greater process flexibility in addition to the benefit of product cooling. In either case a cooling stage is required to bring the product temperature to ambient for stockpiling.

There are conceivably a number of applications of the Gulf Process to low rank coals. While the application for raw coal upgrading requires more detailed technical and economic evaluations, the application of this process to bituminous clean coal appears to be very promising. If the process is integrated into an existing coal operation where middling coal is available as fuel, an order of magnitude estimate of the capital cost for a two-stage Gulf Process is approximately 42 $MM CAN. The operating cost is estimated at $6.0/tonne. With the gain from incremental heating value and savings in dedusting and transportation, a net gain of approximately $0.70 CAN/tonne can be realized. A more detailed analysis is required to confirm this cost and benefit analysis.

In summary, the Gulf Process offers great potential for upgrading marginal thermal coals to meet market specifications for export markets. Future research should concentrate on stabilizing the upgraded products. Both fundamental study of coal chemistry at elevated temperatures and testing of stabilizing options should be investigated.

2. INTRODUCTION

This report describes work performed during 1986-88 on DSS Contract 06SQ.23440-6-9048, "Development of a Method for Upgrading Particulate Coal".

The upgrading method under development by Gulf in this research contract consists of drying low rank coals to below their equilibrium moisture, and treating the dried coals with petroleum residua in a controlled manner. A fixed amount of residuum is injected onto coal particles while they are being dried in a drum dryer. The simple operational feature of this beneficiation method has been demonstrated at the Obed Mountain Coal Company at feed rates up to 150 tonnes/hour, using a conventional BETA-400 Dryer Mixer Plant.

In addition to the study of the process variables of the injection method, the stability of upgraded products was also investigated. Residua were applied in both the neat form and in the form of an emulsion. Products from the injection process were compared with those obtained from the "Immersion" Method which was studied under DSS Contracts 15SQ.23440-3-9024 and 15SQ.23440-4-9062, "The Beneficiation of Low Rank Canadian Coal With Heavy Residuum, Phase I and Phase 2".

This research contract consists of 11 tasks with the following specific objectives:

1. To analyse three different low rank coals identified for process study.
2. To characterize eight different residua used for upgrading low rank coals.
3. To modify the existing drum dryer to allow the studying of various process parameters.
4. To carry out immersion beneficiation experiments to establish beneficiation benchmarks.
5. To investigate various process parameters of the injection method.
6. To investigate the use of asphalt emulsion for low rank coal upgrading.
7. To examine process effectiveness in terms of product qualities, handling properties and product stability.

8. To develop a preliminary conceptual design flowsheet for possible commercial operation.
9. To provide an order of magnitude cost analysis of this beneficiation process.

The results of this research contract are discussed in detail in this Final Report.

3. EXPERIMENTAL

This section describes the equipment and procedures used in the test program.

3.1 Equipment and Operating Procedures

3.1.1 Batch Immersion Method

The batch immersion tests were done in a 28 litre steel tank measuring approximately 30 cm x 30 cm x 30 cm. The tank was electrically heated on the bottom and sides. Approximately 15 litres of residuum in the tank was heated to a desired experimental temperature. The coal was placed in a perforated (3 mm holes) steel basket and spread to a depth of about 3 particles. The basket was slowly lowered into the hot residuum. After 15 minutes of immersion the basket and coal were removed from the residuum. The basket was manually shaken to remove excess residuum from the coal. Also, excess residuum was allowed to drain from the coal while it cooled in the basket. While the coal was cooling it was stirred to prevent formation of a solid agglomerated mass of residuum - bound coal.

The temperature of the residuum was taken immediately before immersion of the coal and ten minutes after immersion while the coal was still submerged.

The treated products were analysed for equilibrium moisture, total moisture, and residuum content.

3.1.2 Continuous Injection Method

Figure 1 illustrates the major components of the continuous unit used to evaluate the injection method. These components are:

1. Gas Burner: Natural gas was used as fuel. The burner was controlled by the dryer exit gas temperature T3. When the set temperature was reached the gas would shut off automatically. If

the gas temperature dropped by more than 5°C within seven seconds, then the gas would come back on, otherwise the delay was 45 seconds. The combustion air remained on at all times.

2. Feed Hopper: The capacity of the feed hopper is 20 kg. Coal was delivered by a vibrating feeder directly into the helical portion of the drying section of the drum.
3. Drum Angle Control: This device was used to change the angle of the drum. Increasing the drum angle reduced the residence time of coal particles in the drum.
4. Drum Drive: The drum was driven by a chain and sprocket arrangement. The drive motor was controlled by an electronic variable speed controller, which enabled the revolution of the drum to be changed. This was a second method of changing residence time of coal particles. Two drum revolutions were used, 9 and 20 RPM (revolutions per minute).
5. Drum Dryer: The 20 cm diameter drum dryer had two sections, drying and mixing. The drying section had an initial 16 cm helical section that slowed down the incoming coal and marginally increased the residence time in the drying section. The second portion of the drying section was 65 cm long and had 16 equally spaced 2.5 cm lifters welded along the inside perimeter of the drum. The 81 cm long mixing section had 8 equally spaced 2.5 cm lifters.
6. Residuum Injection Line: The residuum injection line was a heat traced and insulated stainless steel tube. The injection line was 150 cm in length and 0.95 cm in diameter. Residuum was supplied by a five litre heated pot which fed a heat traced Bran & Leube metering pump which, in turn, fed the residuum injection line. Residuum injection rate could be varied from 0 to 60 g/min. Typical rates used were 7 and 14 g/min.
7. Exhaust: The drying gases were exhausted to the building dust extraction system. There was no mechanism for collecting entrained particulates in the exhaust gases.

The typical operating procedure was as follows:

1. Heat the residuum pot, residuum feed lines and injection lance, and residuum pump to the necessary temperatures (typically 200°C).

2. After reaching the necessary temperature set the residuum pump to the desired feed rate to ensure proper delivery (typically 7-14 g/min).
3. Turn on coal feeder, adjust to desired feed rate, and monitor throughput (typically 20 kg/hr).
4. Adjust drum angle and rpm to give desired residence time.
5. Turn on gas burner and set thermostat control to achieve desired coal product temperature (typically, exhaust gas temperature 50-70°C above desired coal temperature).
6. Allow process conditions to stabilize for approximately 30 minutes after reaching desired product temperature, then take product sample for a period of 5 to 10 minutes.
7. Allow product sample to air cool, then store in sealed container (can or plastic bag).
8. Change process conditions if necessary.

Specific variations to the procedure occurred for:

1. Low oxygen content in the drying gas: The combustion air was reduced and the natural gas input was increased, and nitrogen was injected through a tube inserted in the coal feed chute. Periodically the drying gas was sampled at mid-point of the drum dryer and analysed using a gas chromatograph.
2. Emulsion Injection: The residuum pot, residuum lines and injection lance, and residuum pump were not heated when emulsion was used.
3. Water Cooling: The hot product fell from the treating drum directly into a water bath. The product remained in the bath overnight. The product was filtered and stored in a sealed sample container.
4. Two-Stage Process Simulation: In the first stage, the coal sample was heated in the drum to a desired experimental temperature. The hot coal was air-cooled to room temperature and reintroduced into the hot drum and heated to a new temperature. Residuum was sprayed onto the coal as it passed through the hot drum the second time. The residuum-coated coal was air-cooled and stored in sealed sample containers.

3.2 Stability Tests

Stability of coals and products was evaluated by the CANMET Coal Research Laboratories in Devon, Alberta. The CANMET test determined oxygen sorption and carbon monoxide generation from a sample sealed in a steel cannister after 96 hours. The results are expressed in terms of millilitre/100 gram of sample and parts per million (PPM) for oxygen sorption and carbon monoxide generation, respectively. A stable sample with respect to spontaneous combustion consumes less oxygen and generates less carbon monoxide than a relatively unstable sample.

The CANMET testing procedure was modified to handle coals and products of full size consist rather than the standard 0.25 mm x 0 particles. The modified procedures are as follows:

1. Place 1.5 kg sample in steel cannister of known volume (approximately 21.5 litres).
2. Seal cannister and pass moist air through cannister for 5 minutes.
3. Allow cannister and sealed sample to sit for 96 hours.
4. At end of 96 hours sample air in cannister and analyse for gas composition.
5. Calculate oxygen sorption and carbon monoxide production values.

3.3 Moisture Sorption

In this test, 200 gram samples were placed under a constant environment, 21°C and 75% relative humidity. The weight change due to moisture sorption and desorption was monitored at 24 hour increments up to 96 hours. The weight gain and the rate of weight gain are measures of the sorption propensity towards moisture. This test, in fact, can be considered as a form of equilibrium moisture test under conditions similar to the environments that commercial products would be subjected to.

3.4 Equilibrium Moisture

The equilibrium moisture determination procedure was essentially the same as that specified in ASTM D 1412 with one exception: the full size consist was used instead of the minus 1.18 mm size fraction recommended by ASTM. This change was made because the residuum coating was supposed to seal the outer pores of the particles. Crushing the coated coal would expose fresh untreated surfaces. However, by using the full size consist the chances of sampling error were increased due to sample heterogeneity. This potential problem was compensated for by increasing the weight of sample used per determination, 14-15 grams compared to ASTM's recommended 4-5. Also, for determinations such as those done on the 25 x 12.5 mm coarse immersion products (Section 6) more than 50 grams were used to compensate for sampling errors.

3.5 Product Residuum Content

Representative product samples were pulverized to 0.25 mm x 0. Approximately 3-4 grams of the pulverized sample was placed in a cellulose thimble and a standard Sohxlet Extraction using methylene chloride to determine residuum content on the product. No attempt was made to determine residuum that may have been converted (i.e. Coked) due to the high temperatures in the treating drum.

3.6 Handleability Tests

3.6.1 Dustiness

ASTM D 547 was used to evaluate coal dustiness. A slight departure from the procedure was:

1. Sample weight was 20 kg. The multiplication factor to arrive at the final index values was 50 instead of 40 (i.e. 1,000 kg ÷ 20 kg instead of 2,000 lb ÷ 50 lb).
2. The CMRC design of dustiness cabinet was used, Figure 2, is a modified design of the ASTM cabinet.

The samples evaluated for dustiness are all air-dried samples. They do not contain surface moisture.

3.6.2 Flowability

A National Coal Board Durham Cone test apparatus (Figure 3) was used to evaluate flowability (see Apendix 1 for procedure). Sample weight was 10 kg. Air-dried samples were used in this evaluation.

3.7 Standard Analytical Tests

In addition to the tests described above several standard analytical tests were conducted to characterize the feeds and/or products. These tests included:

- Proximate Analysis : ASTM D 3172
- Ultimate Analysis : ASTM D 3176
- Hardgrove Grindability Index : ASTM D 409
- Calorific Value : ASTM D 2015
- Total Moisture : ASTM D 3302

4. COAL SAMPLES

Three coals were selected for testing. These are:

- Obed Mountain High Volatile C Bituminous, Alberta Foothills
- Highvale Subbituminous B, Alberta Plains
- Poplar River Lignite, Saskatchewan Plains

Tables 1, 2 and 3 present data characterizing the three coals. The Obed coal is a washed and thermally dried product whereas the Highvale and Poplar River coals are raw coals. Thus, the Obed coal is more homogeneous than the other two lower rank coals. With respect to this, analyses done on the latter two coals were subject to greater variation due to sample heterogeneity. This problem cannot be avoided when doing small scale experimentation on raw coals.

Each coal was crushed in a jaw crusher to a top size of 12.5 mm. This was a relatively simple procedure for the Obed and Highvale coals but proved difficult for the Poplar River coal, which tended to break into flat plate-like particles. The Poplar River coal had to be screened and re-crushed several times, which resulted in drying-out of the sample. This occurred to a much lesser extent with the two coals of higher rank. As a result, each of the three coals used for subsequent testing had a moisture content less than its respective equilibrium moisture content.

Tables 4, 5 and 6 provide pertinent data on the three crushed coals used as feedstocks for the bulk of the experimental work described in this report. The equilibrium moistures for Obed, Highvale and Poplar River are 12.2%, 18.5% and 30.5% respectively.

5. RESIDUUM SAMPLES

This section discusses the acquisition/preparation and the analysis of the residuum samples used in the beneficiation experiments.

5.1 Sample Acquisition/Preparation

The following table summarizes the type, source and the pretreatment of the residuum samples. These residua represent a wide range of softening points, viscosities, and calorific values.

Residuum	Type	Source	Pretreatment
Cenex PDA	Asphaltic Crude	Cenex Corporation	None
Clarkson PDA	Asphaltic Crude	Petro Canada's Clarkson Refinery	None
Koch 85-100 Pen Asphalt	Asphaltic Crude	KOCH Materials	None
Thermally Treated Edm. VTB	Conventional Crude	Petro Canada's Edm. Refinery	Thermal Treatment & distillation
CANMET Demo	Heavy Oil	Petro Canada	None CANMET Process
Peace River	Heavy Oil	Gulf Canada DRB Process	Distillation
Suncor	Tar Sand	Gulf Canada DRB Process	Distillation
Coal Tar	Coal	Stelco Inc.	None

Three different kinds of PDA materials were obtained from Cenex Corporation, Petro Canada and from Koch Materials. The different softening points/penetrations of the PDA materials allow the evaluation of these parameters on product qualities.

The thermally treated Edmonton VTB was prepared by Gulf Canada Research and Development in Sheridan Park, Ontario. The vacuum tower bottoms (VTB) from the former Gulf Refinery were thermally treated at 405°C-410°C for one hour. The treated material was separated at 545°C in an EFV Unit (Equilibrium Flash Vaporization) to obtain the residue. The purpose was to increase the softening point of the vacuum tower bottoms generated from a conventional crude.

Both the Peace River (Heavy Oil) and Suncor samples were obtained from the Gulf DRB Process (Donor Refined Bitumen) from the pilot plant in Sheridan Park. These materials were distilled at 545°C for this study.

5.2 Sample Analysis

The results of physical and chemical analyses of the residuum samples are shown in Table 7. The analyses were performed by Alberta Research Council, Coal and Heavy Oil Processing Department in Devon, Alberta. The data includes elemental analysis, metal contents, calorific value, softening point, penetration, density, and viscosity at two different temperatures.

6. IMMERSION METHOD/BENEFICIATION EXPERIMENTS

Previous testwork on the Gulf Process concentrated on applying the residuum by immersing the coal in a liquid pool of residuum (Immersion Method). Operating problems with this method led to the current development for spraying residuum onto the coal (Injection Method). However, it was believed that the immersion method would give superior results with respect to coal upgrading. Accordingly, a series of batch immersion tests were conducted to establish the maximum beneficiation level for each coal and to provide a measure of the effectiveness of the currently proposed injection method.

The test conditions for the batch immersion experiments are outlined below. The replicate tests were selected randomly, with the exception of the Poplar River experiments. A temperature of 200°C was used for the Poplar River lignite replicate tests because of the significant degradation of the lignites at 300°C.

Experimental Conditions:

Residuum Type	:	Cenex PDA
Residuum Temperature	:	200°C, 300°C
Coal Particle Size	:	25 mm x 12 mm
		12 mm x 3.4 mm
Immersion Time	:	15 minutes
No. of Tests	:	6 for Obed high volatile C bituminous
	:	6 for Highvale subbituminous B
	:	6 for Poplar River Lignite

6.1 Observations

Several important observations were made during the batch experiments. They were:

1. The residuum boiled violently upon immersion of the coal. This was due to the water driven out of the coal and vaporizing to steam. The degree of boiling increased as the moisture content of the feed coal increased.

2. The degree of boiling also increased as the residuum temperature increased and boiling was more severe for the fine coal.

3. Foam formation was observed at the residuum surface.

4. The residuum cooled significantly upon immersion of the coal. The heat source was maintained during each test but the source could not supply sufficient heat to compensate for the losses due to vaporization of the coal moisture and heating of the coal itself. Typically, the temperature of the residuum dropped by 40-60°C.

5. The Poplar River lignite degraded significantly during treatment whereas there was no obvious degradation of the Obed and Highvale coals.

6. The method used to remove excess residuum from the treated coal (shaking and draining) was inefficient, particularly for the finer fraction.

6.2 Results

Table 8 presents the results for the immersion tests.

Overall, the results of Table 8 are not consistent with respect to equilibrium moisture reduction, particularly when considering three different coal ranks. Table 8 shows that significantly greater equilibrium reduction occurred for the highest and lowest rank coals, Obed and Poplar River respectively, than for the intermediate rank Highvale coal.

The results for Highvale coal suggest that equilibrium moisture reduction increases as processing temperature increases, but this is not supported by the results from the Obed or Poplar River experiments.

The results for Obed coal suggest that equilibrium moisture reduction increases as particle size increases. This is confirmed by the results for the Highvale coal at 200°C, but is contradicted by the results for Highvale coal at 300°C as well as by all of the Poplar River results. Since the finer

particles had higher initial equilibrium moistures (Tables 1, 2 and 3), it would appear that the immersion process actually gives maximum equilibrium moisture reduction to the finer particles. One would anticipate this result because there is a greater chance for a finer particle be completely heated and saturated with residuum, as compared to a coarser particle whose core might not reach its shell temperature and whose core might not be infiltrated by the residuum.

The friable nature of the lower rank coals, particularly the Poplar River, probably accounts for much of the discrepancy between the Obed coal results and those of the two lower rank coals. A smooth continuous residuum coating was evident on the coarse Obed particles. Not only did the coarse Poplar River particles degrade, but the particles also developed large cracks and crevices. These cracks and crevices opened up the particle interiors and made a smooth continuous residuum coating virtually impossible. Thus, for the lower rank coals the coarser particles were not as well coated, relative to their corresponding finer particles. On the other hand, these cracks and crevices are partially filled with residuum, which partially accounts for the high product residuum contents of the lower rank coals. Since pore size and volume increases as coal rank decreases, one would expect product residuum content to increase as coal rank decreases. This expected trend is confirmed by the results in Table 8. In addition, the size degradation that occurred for the lower rank coals created additional particle surface area and this also increased product residuum content.

Product residuum content is greater for the finer particles. This is to be expected due to the larger surface area of the finer particles and their ability to trap residuum within the particle bed. Poor drainage accounts for the higher product residuum contents that occur at the lower processing temperature. Residuum viscosity is higher at lower temperature.

It is not obvious from the results that product residuum content affects product equilibrium moisture. The results for Obed coal (Table 8) give no indication of this trend (compare the two Fine 300°C or the two Coarse 300°C) nor do the Highvale results (compare the two Fine 200°C or the two Coarse 300°C). The results of Poplar River fine lignite at 200°C suggest that higher residuum content does reduce equilibrium moisture, but this trend was not observed for the coarse lignite at 200°C.

It should be noted that there is one consistent trend in all the results that actually contradicts expected behaviour: the coarse particles consistently have lower product moisture contents than the fine particles. This is unexpected because the core of a coarse particle will not heat up as quickly as the core of a fine particle. Also, the moisture must travel farther to be removed from a coarse particle as compared to a fine particle.

7. BENEFICIATION EXPERIMENTS USING THE CONTINUOUS UNIT BY INJECTION METHOD

Table 9 outlines the design of the experimental program used to evaluate the injection method of beneficiation, using the continuous Pilot Drum Unit. A complete list of experiments is provided in Appendix 2. A total of 102 experiments, significantly more than the sixty four experiments originally planned, were carried out in this research contract.

7.1 Preliminary Testing of Process Variables

The purpose of the preliminary testing was to select variables that were significant on product quality. A number of process variables were identified as being potentially significant with respect to product quality. Using equilibrium moisture as the main product quality evaluation criterion, the following variables and the levels tested in the preliminary testing using Obed coal were as follows:

Variable	Levels Tested
Product Temperature	200°C, 300°C
Residuum Application Rate	2%, 4%
Residence Time	6 min, 12 min
Particle Size	12.5 x 0 mm, 12.5 x 1.7 mm
Pre-drying to Mixing Ratio	1:1, 4:1
Drying Gas Oxygen Content	<5%, >15%

The test results (Table 10) indicate that, over the range of levels tested, residence time, particle size, and pre-drying to mixing ratio have virtually no effect on equilibrium moisture. It is important to recognize that these conclusions are derived for the ranges of variables studied in this program. It should also be pointed out that pre-drying to mixing ratio affects the product residuum content, but not the equilibrium moisture. Reducing the ratio requires either addition of the residuum farther inside the drum, closer to the hottest drying gases, or extending the mixing section which means the treated coal remains in the hot gases for a longer period of time. In either case, more residuum is consumed through oxidation in the drum. Also, residence time is limited by the need to achieve desired product temperature.

The test results in Table 10 showed that product temperature, residuum application rate, and drying gas oxygen content did affect product equilibrium moisture.

Increasing product temperature decreases product equilibrium moisture, product residuum content, and product moisture.

Decreasing drying gas oxygen content increases product residuum content and decreases product equilibrium moisture. There is no effect on product moisture content. Low drying gas oxygen content was achieved by increasing the fuel (natural gas) to air ratio and by injecting nitrogen downstream of the flame.

The obvious effect of decreasing residuum application rate is to reduce product residuum content. Residuum content has a minor effect on equilibrium moisture. A significant effect would be anticipated over a wider range of application rates. Also, there are other critical product characteristics, notably stability (see Section 7.8) that are significantly affected by residuum application rate.

7.2 Confirmation Tests

The purpose of the second series of tests was to confirm the effects of product temperature, drying gas oxygen content, and residuum application rate, using Obed coal and a different PDA (Clarkson). Table 11 presents the results of these tests.

The results confirm the effects of product temperature. The effects of drying gas oxygen content are inconsistent with respect to product equilibrium moisture but confirm that lower oxygen content in the drying gas gives higher product residuum contents. There was also a significant difference in product appearance when oxygen content was varied in the drying gas: the low oxygen condition yielded a dull product and the high oxygen condition yielded a bright shiny product.

The effect of residuum application rate was also confirmed in the second test series. (Comparison of residuum treated products to non-treated

products provides a better indication that the residuum does affect product equilibrium moisture.) Higher residuum application rates give products of lower equilibrium moistures.

On the basis of the preliminary and confirmation tests, standard test conditions were established for subsequent testing. These conditions were:

- Particle size range of 12.5 mm x 0
- Pre-drying to mixing ratio of 1:1
- Residence time of 12 minutes
- Drying gas oxygen content >15%

Of these standard conditions, only the effect of the oxygen content in the drying gas was not fully established. A high oxygen content in drying gas was selected due to the difficulty in maintaining low oxygen gas content over the wide range of conditions being evaluated. In addition, the high carbon monoxide levels in the drying gas, at low oxygen content, presented a health hazard. Occasionally, low drying gas oxygen content conditions were run to further evaluate this variable. Such test results are indicated where pertinent. These latter results did not clarify the effect of drying gas oxygen content, except to confirm that higher product residuum levels result at low drying gas oxygen content.

7.3 Effect of Residuum Type

A separate series of tests was carried out to evaluate whether residuum type affects product quality. Obed coal and the eight residua described in Section 5 were used in this test series. The test conditions for each residuum are summarized below:

Conditions

- 200°C product temperature, 12 min residence time, 4% residuum, oxygen content >15% in drying gas
- duplicate tests at the conditions mentioned above
- 300°C product temperature, 12 min residence time, 4% residuum

The test results are presented in Table 12 and in Figure 4. The results indicate that no single residuum is significantly better than the others and all residua produce products of similar quality. Despite the similarity in results, one would predict that at lower temperatures the residua of higher softening point will not efficiently coat the coal or penetrate the coal pores, and conversely, at higher temperatures the lower softening point and higher volatile content residua will be less effective due to the increased oxidation/volatilization losses.

The scope of work called for selection of the best residua for further testing with the two lower rank coals. However, it was impossible to test all eight residua with the two lower rank coals within the scope of work. Consequently, the following four residua were selected for subsequent testing:

1. Cenex PDA: selected on the basis of availability and because of the large number of tests already done using this residuum. Also, this residuum had been previously used for a major field trial.
2. Clarkson PDA: selected on the basis of having the best overall test results as well as the reasons for selecting Cenex PDA.
3. Peace River: selected due to its high softening point and due to the excellent test result for the 300°C product test.
4. CANMET Demo: selected due to its high softening point and because of its generally less desirable test results in the preliminary evaluations. It was important to establish whether poor results were a characteristic of the residuum or simply coal specific.

The testing conditions used for the four selected residua with the two lower rank coals are summarized below:

	Test Conditions			
	Product T °C	Residuum Appl. Rate, %	Residence Time, min.	Drying Gas O_2, %
1	200	2	12	+15
2	200	4	12	+15
3	300	2	12	+15
4	300	4	12	+15

The test results presented in Table 13 tend to confirm the results presented in Table 12. This is more evident for the Highvale coal than for the Poplar River coal.

There appears to be an interaction between product temperature and residuum. Table 14 shows that at 200°C the four residua produce similar results (the Cenex appears better but this is largely due to the single Poplar River result) but at 300°C the Clarkson PDA and the Peace River give consistently better results than the Cenex PDA and CANMET Demo.

7.4 Effect of Temperature

The effect of temperature is clearly demonstrated in Table 15 and Figure 5 as well as in Tables 12 to 14, inclusive. Higher temperature (300°C) is beneficial in the reduction of equilibrium moisture. Operating the Gulf Injection Process at 200°C only gives marginal reduction of equilibrium moisture. The effect is observed for all the coals studied in the program.

7.5 Effect of Residuum Application Rate

Table 16 indicates the effect of residuum application rate on product equilibrium moisture. These results confirm those of the preliminary tests: the effect is minor.

7.6 Effect of Coal Rank

The Obed, Highvale, and Poplar River coals are characterized in Section 4. With respect to their behaviours in the continuous process, only the Poplar River gave problems. At 300°C product temperature the Poplar River temperature was difficult to control due to the coal's reactivity. There was also noticeable size degradation for the Poplar River coal.

The results presented in Table 17 indicate that there is no linear relationship between coal rank and equilibrium moisture reduction achieved through the continuous process. The Highvale coal was least affected of the three coals.

7.7 Optimum Products Tests

Three tests were run, one with each coal, at conditions considered to be optimum with respect to equilibrium moisture reduction. The test conditions for each coal were:

- 300°C product temperature
- 4% applied residuum, Clarkson PDA
- 12 min. residence time
- drying gas oxygen content > 15%

A product temperature of 300°C was selected because this temperature gave the maximum reduction in equilibrium moisture for each coal. Higher temperatures would likely further reduce equilibrium moisture but 300°C was selected since it was the highest temperature used in previous tests.

Similar reasoning led to the selection of 4% residuum application rate. The Clarkson PDA was selected on the basis that it was one of the best residua, particularly at high temperature.

A residence time of 12 minutes was selected to ensure complete heating of the larger coal particles. A 1:1 pre-drying to mixing ratio was selected to provide for maximum coating efficiency. These two conditions had been used for essentially all prior testing.

High drying gas oxygen content was used because of the difficulty in maintaining low oxygen content for prolonged periods and because the effect of drying gas oxygen content was inconclusive with respect to product equilibrium moisture.

The "optimum" products were evaluated with respect to:

- equilibrium moisture
- total moisture
- % residuum
- calorific value

- size distribution
- moisture sorption
- handling properties (dustiness, flowability)
- stability

Tables 18 to 24 present the results of the "optimum" conditions tests. The results confirm that the process has a much greater effect on Obed and Poplar River coal than on Highvale coal.

7.7.1 Equilibrium Moisture

The basic quality data for the upgraded products are shown in Table 18. Compared to the feedstocks, reductions in equilibrium moisture for the Obed coal, the Highvale coal, and the Poplar River lignite are 26.4%, 18.9% and 35.1%, respectively. Residuum contents determined on the products are similar for Obed and Highvale (1.6 - 2.0%), but much higher for the lignite (3.6%).

The reasons for the much higher residuum content on the lignite products are not clear.

7.7.2 Calorific Value

The calorific values presented in Table 19 indicate that the Poplar River coal received the greatest upgrading. The dry, ash-free calorific values of all products were higher than the corresponding values of the parent coals. This indicated the presence of residuum and the elimination of certain oxygen species in the parent coals.

The moist ash-free calorific values show the benefits attributable to the combined effects of equilibrium moisture reduction, the presence of residuum, and conversion of the coal due to temperature. The moist ash-in values show typical product calorific values assuming the products regain moisture to equilbrate with the environment. For the purposes of Table 19 this environment is assumed to be 21°C and 75% relative humidity. The product moisture values for such an environment are indicated in Table 20. Again, lignite has the highest increase in calorific value on this basis.

7.7.3 Moisture Sorption

In a commercial operation the products would not re-sorb moisture to their equilibrium moistures (96% relative humidity, 30°C). The moisture sorption results of Table 20 show the moisture gains and losses in an atmosphere of 75% relative humidity and 21°C, which more closely approaches normal ambient levels. This table indicates that although the process produces virtually bone-dry products, the products will re-sorb moisture from the atmosphere. This factor is expected to create stability problems due to heat of wetting. The greater the difference between product equilibrium moisture and actual product moisture, the greater will be the potential for stability problems related to heat of wetting.

7.7.4 Stability

Table 21 provides additional information relating to stability. The data shows that the products are more reactive than their feeds, the only anomaly being the lower oxygen sorption of the Poplar River product relative to its feed. These results are discussed in more detail in Section 7.8.

7.7.5 Handleability

Table 22 shows that the processed coals are significantly less dusty than their corresponding feeds. It should be noted that both the feeds and products were surface dry. The feeds would not be saleable in such conditions whereas the products would be, with the possible exception of the Poplar River product. Table 23 shows the size distributions of the feeds and products. For the Obed and Highvale coals there is a significant reduction in the minus 100 mesh (0.15 mm) size fraction, which accounts for the reduction in dustiness. The Poplar River feed and product have similar quantities of minus 100 mesh (0.15 mm) particles, yet the product is significantly less dusty than the feed, indicating that the extremely fine particles (i.e. minus 325 mesh (0.045 mm)) have either been bound to the coarser particles by the residuum or they have been combusted in the drum dryer.

Table 23 shows that the Obed coal does not break down during processing whereas the Highvale and Poplar River coals do. This agrees with the observed effects of the immersion process. It also suggests that for the lower rank coals the long term effectiveness of the residuum coating is very important. If the coals continue to break down due to weathering, as lower rank coals are known to do, then the long term dust suppression effectiveness of the residuum will be reduced. On the other hand, it is possible that the processing has so altered the coals that further degradation will not occur. This potential benefit of the process was not evaluated.

The feeds and their corresponding products have similar flow characteristics (Table 24). It should be noted that the feeds were evaluated for flowability at the same surface dry conditions as for dustiness. At surface moistures that would make the feeds acceptable with respect the dustiness their flow properties would be somewhat poorer. Thus, flowability benefits attributable to the process are somewhat greater than those suggested by Table 24.

7.8 Product Stability

Table 25 presents the results of stability evaluations on the feeds and numerous products. As previously mentioned (Section 7.7) the products exhibit reduced stability relative to their corresponding feeds. The residuum application does improve product stability relative to no residuum application (Test #6 vs. Test #7) , but the improvement is not sufficient to overcome the increased activity created by heating the coal.

Table 25 also presents stability evaluation results for Obed coal subjected to various process conditions. The Test #8 results indicate that product stability is enhanced at low drying gas oxygen content because more residuum remains on the product under such condition. The Test #9 results indicate that water is an effective means of improving product stability. This suggests that the difference between product equilibrium moisture and product moisture is more critical than equilibrium moisture by itself. The product of Test #9 was obviously too wet to be acceptable. More work is required to establish the full effect of product moisture on stability. Also, the effect of product moisture distribution, surface water versus "internal" water, deserves further investigation.

Tests #10, #11 and #12 indicate that there is no stability benefit attributable to using emulsion (see Section 8). Indeed, the emulsion test results are somewhat poorer than the results for the neat asphalt, Test #10. This is somewhat surprising since increasing both residuum content and moisture content were shown to improve product stability. In Test #12, the coal was heated in a first stage, then cooled to room temperature, and then the residuum emulsion was applied. This processing method results in higher product residuum content and moisture content, yet there is no improvement in product stability.

The question of product stability is critical and more work is needed to further define the potential benefits of the various process options.

8. BENEFICIATION EXPERIMENTS USING ASPHALT EMULSIONS

This section discusses the results of beneficiation experiments using asphalt emulsions. Preparation of emulsions from residua of different properties, and beneficiation experiments using the prepared emulsions were proposed in the original work statement. Preparation of emulsion, however, requires special equipment and expertise; and it is also important to first establish the technical feasibility of asphalt emulsion in beneficiation before the actual preparation. Consequently, the work statement was revised with the main objective to establish the technical merits of asphalt emulsion. A commercially available asphalt emulsion was acquired for this purpose.

8.1 Beneficiation Experiments

The Koch 85/100 asphalt emulsion, a 55% asphalt and 45% water emulsion was used in the beneficiation experiments. The base asphalt was the Koch 85/100 asphalt used in Section 7. The base asphalt has a penetration of 77, and the emulsion of this asphalt is commercially available.

The results of the beneficiation experiments are summarized in Table 26. The results suggest that the product qualities from the asphalt emulsion and neat asphalt are similar. It should be noted that in order to have approximately the equal residuum content on the products, the rates of application must be doubled for the asphalt emulsion relative to the pure asphalt. Although difficulties were encountered in the injection of asphalt emulsion due to water evaporation, there was little difference between the products from asphalt emulsion and from asphalt in its natural form.

8.2 Process Flexibility Using Emulsion

There are benefits to using emulsion that are related to process flexibility. The results of evaluating processing alternatives for emulsion are presented in Table 27. The emulsion enables the asphalt to be applied to cold coal, as was done for Tests #7 and #8 of Table 27. The coal was heat treated, then cooled to room temperature, and then treated with emulsion. This has the advantage of maximizing the amount of asphalt that remains on the product since

there is no asphalt consumption due to hot drying drum gases. There is also the advantage that the emulsion helps to increase product moisture. The earlier discussion of product stability, Section 7.8, indicated that both of these factors improve product stability, although the limited stability testing done with the emulsion did not confirm these hypotheses (Table 25). The results of Table 27 tend to confirm those of Table 26: emulsion does not increase equilibrium moisture reduction. Nevertheless, the processing flexibility afforded by the emulsion is a significant benefit.

9. COMPARISON OF IMMERSION AND INJECTION METHODS

The immersion method (Section 6) was used to establish a beneficiation benchmark. This benchmark was used to evaluate the effectiveness of the injection method (Sections 7 and 8). Figure 6 illustrates some of the major similarities and differences between the two methods, particularly with respect to their effect on equilibrium moisture. Comparison of the products of the two methods indicates the following important differences:

1. The immersion method gives a significantly greater degree of reduction in equilibrium moisture at comparable residuum content.
2. The immersion method results in significantly higher residuum levels on the products, because of the difficulties in residuum draining.
3. Processing temperature was not as significant in the immersion method.
4. Handling of the products from the immersion method was much more difficult due to the high product residuum levels.

The test results indicate the following significant similarities:

1. Highvale coal is least affected by processing.
2. Product residuum content has a minor effect on equilibrium moisture reduction.
3. Particle size degradation increases as coal rank decreases.

It should be noted that no stability evaluations were done on the immersion method products. The lower product equilibrium moistures and higher product residuum contents of the immersion products would likely result in improved product stability relative to products from the injection method.

10. CONCEPTUAL DESIGN & CAPITAL ESTIMATE

This section discusses the general processing conditions of the Gulf Process, the expected product characteristics, the options for process operation, possible process applications, and a conceptual design with order-of-magnitude estimates of capital.

10.1 General Processing Conditions

The experimental program in this research contract studied a number of process variables; eight different types of "residuum," one commercially available emulsion of asphalt, and three different coals (lignite, subbituminous, and high volatile C bituminous). While the effects of the process variables are fairly well defined, the optimum processing conditions for each individual thermal coal are not completely established, particularly with respect to product stability.

The response of the Obed bituminous coal, which was studied in this research contract and a number of other contracts sponsored by various parties, is better understood than the Highvale subbituminous coal and the Poplar River lignite. The general processing conditions of the Obed coal, therefore, are used as the base line data for the conceptual design of a coal beneficiation plant.

The experimental data of this research contract showed that processing temperature is the most important factor in the Gulf Process for equilibrium moisture reduction. Higher processing temperatures are beneficial in reducing equilibrium moisture. On the other hand, higher temperatures will decompose coal components that are thermally unstable, thereby reducing the volatile matter content of the product. For coals of bituminous ranks a processing temperature around 300°C appears to be optimum in terms of reduction of pore volume and retention of volatile matter. The processing temperature for subbituminous and lignitic coals require further optimization of process variables.

The experimental data also showed that the "residuum" levels on products do not have a large effect on equilibrium moisture reduction, although higher residuum level does help to stabilize the upgraded products. Since petroleum pitch is an important cost component in the Gulf process, a lower pitch

level will greatly enhance the economic viability of the Gulf process. Four percent pitch level on bituminous coal product is generally considered as the optimum value. Lower rank coals, which have a high equilibrium moisture, may require higher pitch levels. To further improve the utilization of petroleum pitch, a two-stage operating scheme is currently being investigated by Gulf in the coal development program. A brief description of this process sequence is given in Section 10.3.

It is obvious from the experimental program that the effect of residence time on product qualities is minimal. A residence time of ten minutes is therefore selected as the base line condition. This residence time is also expected to be appropriate for coals of lower ranks.

While in the laboratory scale the cooling of hot products has never been a problem, in actual operation a cooling system is required to quickly lower the product temperature from the 300°C range to ambient temperature for stockpiling. Both air and water can be utilized as the cooling medium. Water cooling is preferred because this option will provide an additional benefit to the process. During water cooling, the products will absorb water internally to reduce the gap between residual moisture and the equilibrium moisture, and adsorb water externally to enhance the stability of the product coals. A 10 to 15 minutes residence time in water cooling in a two-stage operation will be sufficient to bring the products to ambient temperatures.

10.2 Expected Product Characteristics

The product characteristics in terms of quality, handling properties, and stability with reference to the feedstock are summarized below for bituminous coals.

Based on a feedstock of bituminous coal of 12-14% equilibrium moisture the upgraded product will typically show an equilibrium moisture of about 7%, and a product moisture of 1%. With water cooling, the product will have a total moisture around 8%. Such a product will have a calorific value exceeding 6,000 cal/gm. For marginal thermal coal with respect to heating value, the improvement of heat content over 6,000 cal/gm has a significant impact on marketing. For coals

of lower ranks, the improvement of heating values to the 6,000 cal/gm region will remain difficult, principally because of the low heating values of the feedstocks. Lower rank coals have higher oxygen content which does not contribute to the heating value.

Ash level and volatile matter content of the products are comparable to the feedstock. These will ensure that the combustibility of the products will not be significantly altered. The products have higher concentrations of carbon, hydrogen, and sulphur because of the addition of pitch materials.

In terms of the handling properties, upgraded products show significant reduction in dustiness and are comparable to their feedstocks in flowability. The essential elimination of the dusting problem will offer a definite advantage in coal marketing.

Upgraded products are also comparable to their feedstocks in terms of product stability. While residuum addition will reduce pore volume, higher processing temperature may also create "active sites" or free radical species which are more prone to oxidation. Improving the stability of products will be emphasized in the future development program.

10.3 Process Operation Options

Most of the experiments in this research contract were carried out in a single-stage operation: heating the coal and spraying petroleum onto coal particles at the same time in a pilot drum dryer. Both petroleum pitch and asphalt emulsion were used in this mode of operation. A sketch of the single-stage operation is shown in Figure 1.

This mode of operation is technically feasible but suffers from loss of pitch and possible conversion of pitch into petroleum coke at elevated temperature. Nevertheless, the technical feasibility of this mode of operation was proven through a series of field tests conducted in 1986 at the Obed Mountain Coal Company.

In order to maximize the utilization of petroleum residuum, Gulf initiated a program to investigate the process in a mode of two-stage operation. The two-stage operation consists of heating the coal in a drum dryer to desired temperature, and coating the hot dried coal at a reduced temperature in a second treating drum. Results of this development program showed that comparable product qualities are obtained at lower application rates of pitch materials.

The two-stage operation gives considerable process flexibility and offers effective utilization of pitch materials. A sketch of the two-stage operation is presented in Figure 7.

10.4 Possible Process Applications

It has been shown in this research contract and contracts supported by other parties that the heating value of low rank coals can be enhanced by the Gulf Process. It is also noted that by applying petroleum pitch, the dusting problems are essentially eliminated. A scenario for the possible applications of the Gulf Process is provided in this section.

The application of the Gulf Process to bituminous clean coal targetted for export markets appears to be of the greatest potential, provided that the stability of the products can be improved to levels comparable to bituminous metallurgical coals. In other applications, it is recommended that the technical feasibility be studied and the economic viability be critically assessed. In addition, the fit of product qualities for utilization technologies, the market specifications, the needs of individual producers, and the strategies of fossil fuel development will all play an important role in determining the appplications of the Gulf's Beneficiation Process.

10.4.1 Raw Coal Upgrading

The Gulf Process can be applied to low rank raw coals primarilly for moisture reduction. For producers of subbituminous coals and lignites, which are mainly utilized in mine-month power generating stations, the Gulf Process should help to deliver a product of very low moisture content to the power plants. These

low moisture products should increase the boiler efficiency. This application depends on the immediate utilization of the upgraded products, assuming the products are as reactive or even more reactive than their parent coals.

The upgraded products from this application are not expected to meet the specifications set for thermal coals for the export markets. They are probably not an ideal fuel for distance markets given the stability concern. Further processing of the Gulf products into form fuels (pellets or briquettes) deserves some investigation, because it will help stabilize these products for transport by utilizing the excellent binding power of the pitch materials used in the Gulf Process.

In areas where low rank coals are abundant and low cost heavy oil residua are available, the simultaneous utilization of two indigenous resources will be highly acceptable. The pitch material, otherwise a process burden in heavy oil operation, can be utilized to enhance the heating value of the coals for power generation.

10.4.2 Clean Coal Upgrading

The clean coal products from bituminous coal operations are ideal candidates of the Gulf Beneficiation Process. The upgraded products with suitable stability will meet or exceed the specifications for thermal coals for the export markets. The availability of processing equipment and the established coal mine infra-structure will also enhance the economic viability of the applications.

Clean coals in the form of dryer feed can be routed directly to the Gulf Process. Both the single-stage and the two-stage operations can be utilized. While the single-stage mode of operation was field tested at up to 150 tonnes per hour in 1986, the application of the two-stage operation is expected to give products of similar qualities with the benefit of more efficient utilization of pitch materials, which are currently available from propane deasphalting units (PDA).

Besides processing the clean coals available as dryer feed, the Gulf Process could also be integrated into the coal preparation plants by utilizing the existing Rotary Kiln Dryer or Fluidized Bed Dryer, if available. One option is to

modify the Rotary Kiln Dryer/Fluidized Bed Dryer to the Gulf processing temperature range. The second opportunity would be to utilize the existing Rotary Kiln Dryer as the treating drum. The modification of the Rotary Kiln Dryer to a treating drum requires less severe changes due to the lower temperatures required. Both asphalt and asphalt emulsion could be used in the latter case.

10.5 Conceptual Design of a Coal Beneficiation Plant and Estimates of Capital Cost

This section presents a conceptual design of a coal beneficiation plant based on Gulf's Technology and comments on capital cost estimates. The case selected for discussion is a clean coal dryer feed from a bituminous coal preparation plant where existing facilities are available. The comments on capital cost are based on an operation of three million tonnes per year of feedstock.

10.5.1 Conceptual Design of a Coal Beneficiation Plant

A flow diagram for a two-stage coal beneficiation plant is shown in Figure 8. Six main components are involved. They are briefly discussed below:

- Feed Preparation Systems

  This area includes handling of dryer feed clean coals and the pitch feeding system. Equipment required are feed bins, conveyors, etc.

- Drying Drum

  The drying drum will be operated in the temperature range of 300°C to achieve maximum reduction of equilibrium moisture. Coal particle residence time in the drying drum will be on the order of ten minutes. Dryer product is expected to exit the drum at approximately 300°C. Heat source for the drying drum will be middling coals from the preparation plant.

- Treating Drum

  The product exiting from the drum dryer will be coated in a treating drum with pitch material at approximately 4wt% based on product. A residence time of ten minutes is used to evenly spread the pitch onto coal particles. Products exiting the treating drum would be at approximately 150°C. There will be no heat source for the treating

drum, but residual heat carried over from the dryer drum will be utilized.

- Cooling & Stabilization Devices

  The products from the cooling drum will be cooled in water to lower the product temperature and stabilize the products. It is expected that product temperature of 30°C can be reached at about ten to fifteen minutes residence time. The product leaving the cooling and stabilization devices is expected to have a total moisture of 8%.

- Flue Gas Handling

  The flue gas generated in the heating drum will be largely steam from moisture evaporation but will be contaminated by fine coal dust particles and some hydrocarbons. The flue gas generated in the treating drum will be mainly hydrocarbons distilled off the pitch materials. A Venturi Flue Gas Scrubber System and perhaps an Incinerator will be required so that both particulate emission and gas emission specifications will be met.

- Product Loadout and Stockpiling

  Bins, conveyor etc. for product loadout and stockpiling.

10.5.2 Comments on Capital Cost Investment

This section gives a very rough capital cost estimate based on a three million tonne per year Feedstock Beneficiation Plant. Since the experimental program provides very little project definition except the base line conditions to be used, the comments on capital cost are very preliminary in nature. Based on 200 operating days of 24 hours, the capacity of drum dryer required is 625 tonnes/hr of dryer feed. Since this process will be incorporated into an existing coal preparation plant, cost for building, roads and cooling water, are excluded in the estimate.

A conventional asphalt dryer mixing plant capable of drying coal at 225 tonnes/hr per unit costs about 1.2 million Canadian dollars. This cost is used as the base for the capital cost estimates. The total cost for a Coal Beneficiation Plant is estimated at 41.8 MM $CAN. The following table shows all the adjustments that are required for estimating the capital cost of such a Coal Beneficiation Plant.

Adjustment Factor	Adjusted Value (MM $ CAN)	Remarks
		1.2 MM for a conventional asphalt dryer at 225 tonnes/hr capacity.
1.45	1.74	Metallurgy cost factor to allow drum dryer to operate at 300°C
2.0	3.48	Allows for cost of one additional treating drum and one additional cooling drum
3.0	10.44	Capacity factor for 625 t/h (3 units at 225 t/h)
4.0	41.76	Factors for miscellaneous items i.e. middling coal for heat generation, coal burners, ash handling, utility connection, winterizing etc.

If natural gas is used to provide the process heat, a factor of 2.5 is probably sufficient to cover the adjustments for miscellaneous factors. This will bring the total capital cost to 26.2 million $CAN. It should be noted when natural gas is used, the operations cost will be higher, since middling coal is assumed to have zero value in a coal preparation plant. The operating cost is discussed in the next section of this Final Report.

11. PROCESS COST REVIEW

This section gives an order of magnitude estimate of the operating cost of the 3MM tonnes/year Coal Beneficiation Plant. The values of the upgraded product and the feedstock are also compared.

11.1 Operating Costs

Each component of the operating cost for this coal Beneficiation Plant is estimated below. When middling coal is used to provide process heat, the total operating cost is estimated at 6.0 $/ton. When natural gas is used as the heat source, the operating cost is estimated at 7.4 $/ton. In both cases the pitch cost is the largest component in the operating cost: 84% and 68% for middling coal and natural gas fuel operations, respectively.

Cost Component	$ CAN/Tonne Middling Coal for Process Heat	$CAN/Tonne Natural Gas for Process Heat	Remarks
Electricity 700 kw/225 TPH at 0.03 $/KWH	0.09	0.09	
Make up water for scrubber and cooling	0	0	Available from existing coal preparation plant
Fuel Cost	0	1.68*	Middling coal at zero value; Natural gas at $2.50/GJ
Labor cost 4 persons/shift 3 shifts/day $40,000/year	0.16	0.16	
Pitch Cost at $15 US/Barrel 1 CAN $/0.75 $ U.S. Barrel/159 Kg 4% Pitch on product	5.03	5.03	
Capital Charge 5% of Capital Cost	0.70	0.44	
TOTAL OPERATING COST	5.98	7.40	

*Calculated from the following Table "Estimate of Process Heat Requirement"

Estimate of Process Heat Requirement

ASSUMPTION: Feed coal at 20°C, 14 wt % moisture
Pitch applied at 200°C, 4 wt % of product
Product at 300°C, 2% moisture, 90% yield
Off Gas at 300°C, 2% yield
Moisture 300°C, 10% yield
No recovery of heat during product cooling

Process Stream	Heat Content (Cal/kg)	Calculations
Feed	0	(M x Cd x T) (Mass x Specific Heat x Temperature Difference)
Residuum	2,880	0.04 x 1,000 x 0.40 x (200 - 20)
Moisture	73,500	.10 x 1,000 1.0 (100 - 70) + 555 + 0.5 (300 - 100)
Off gas	1,736	.02 x 1,000 x 0.31 x (300 - 20)
Product	88,200	.90 x 1,000 x 0.35 x (300 - 20)

TOTAL HEAT REQUIREMENT = (88,200 + 73,000 + 1,736) - (0 + 2,880)
= 160,556 Cal/kg

1 TONNE OF FEED REQUIRES 160.55 x 1,000 x 4.186 x 10^{-6}
= 0.672 GJ of Heat

11.2 Comparison of Product and Feedstock Values

The value gained by product by beneficiation is compared in the following Table. The value gain is calculated by using the value of incremental heating value, the saving in transportation cost, and the saving in dust suppression. The value gain for a typical bituminous clean coal is $6.72/ton more than enough to pay for the operating cost based on Middling coal fuel ($5.98). The net gain is $0.74/tonne.

	Feed Stock (Reference)	Product
Weight Basis	1.00 tonnes (14% Moisture)	0.995 tonnes
Heating Value (kcal/kg)	5,600	6,200
Value gain ($) from incremental heating value at 1.02 $CAN/100 kcal/kg	---	+6.09
$ Saving from dust suppression at $ 0.5/ton feedstock	---	+0.50
$ Saving in transportation cost at $ 25/ton	---	+0.13
$ Operating Cost/Tonne	---	(-5.98)
TOTAL NET GAIN $ CAN/Tonne		+0.74

12. CONCLUSIONS

The following can be concluded for this research contract:

1. The immersion process provides significantly greater equilibrium moisture reduction for all ranks of coal than does the injection process at comparable residuum levels; however, the operating problems and the high residuum consumption of the immersion process make it technically difficult and uneconomic.

2. Beneficiation by the Injection Method, in terms of the degree of equilibrium moisture reduction, is coal specific and is not a direct function of coal rank. Equilibrium moisture reductions at "optimum" conditions for the Obed, Highvale, and Poplar River coals were 26.4%, 18.9% and 35.1% respectively.

3. Due to the addition of residuum and possible elimination of oxygen species in the Injection Method, the calorific values on the dry ash free basis are 6,730 cal/g, 6,940 cal/g and 7,540 cal/g for Poplar River lignite, Highvale, and Obed products respectively. The corresponding values for the parent coals are 6,470 cal/g, 6,850 cal/g and 7,470 cal/g.

4. Products from the Injection Method readily reabsorb moisture at 21°C and 75% relative humidity. Weight gains are 5.7%, 10.1% and 12.9% for Obed product, Highvale product, and Poplar River product, respectively, in a period of 72 hours.

5. The Injection products are significantly less dusty than their parent coals. The coarse dustiness index values are 4.5, 13 and 99 for Obed, Highvale, and Poplar River, respectively. The corresponding values for the parent coals are 105, 246 and 257.

6. There are no significant differences in the flowability of the products when compared to their parent coals.

7. The products from the Injection Beneficiation Method are less stable than their parent coals, when evaluated by the CANMET Oxygen Sorption Method. Products consume more oxygen and produce more carbon monoxide in this laboratory stablity evaluation test.

8. The Injection Method with low oxygen content in the drying gas appears to improve product stability. Product stability also improves when the difference between equilibrium and product moisture narrows.

9. Regardless of coal rank, temperature is the most significant factor in the Injection Method. At 200°C only marginal reduction in equilibrium moisture is achieved. At 300°C, substantial reductions in equilibrium mositure are realized for all ranks of coal.

10. Over the range of 0 to 4%, residuum application rate has only a minor effect on product equilibrium moisture; however, residuum application rate significantly affects other product properties such as calorific value, dustiness, and stability.

11. Type of residuum and residuum properties have very little effect on product equilibrium moisture. Residua from all sources are suitable in the Injection Method.

12. Asphalt emulsion does not improve equilibrium moisture reduction relative to neat asphalt; however, the emulsion offers processing options not available with neat asphalt.

13. An order-of magnitude estimate for capital cost based on 3 million tonne per year of feedstock in an existing coal plant, is 42 million $ Can, using middling coal to provide process heat. If natural gas is used as fuel, the capital cost is estimated at 26 million $ CAN.

14. The operating cost of the Gulf Injection Process is estimated at 5.98 $/tonne, based on middling coal used as fuel, and

7.40 $CAN/tonne based on natural gas. Residuum cost is the main component in the operating cost, 84% and 68% for middling coal and natural gas operation, respectively.

15. Process operating costs for the continuous process, $5.98 per tonne, are projected to be less than the increased revenues attributable to improved beneficiated product, $6.72 per tonne.

16. A two-stage process, heating followed by residuum application at reduced temperatures, will result in increased recovery of residuum on the product, about 80-90% recovery versus 40-50% for a single-stage process for a product temperature of 300°C.

13. RECOMMENDATIONS

Product stability remains the most critical unsolved problem. Efforts should concentrate on this aspect of the product properties. Specific recommendations with respect to product stability improvement include:

1. Continued development of a two-stage process designed to maximize the amount of residuum retained by the products.

2. Evaluation of low oxygen content atmospheres, such as steam, in the treating drum, in order to reduce residuum oxidation and coal surface oxidation, and to help stabilize the products.

3. Evaluation of additional treatments, such as CO_2 cooling of the hot treated product, in order to help stabilize the product.

4. Study of the chemistry of thermally treated coals to understand their reactivity towards oxidation. This may lead to the development/selection of inhibitors for product stabilization.

Table 1

OBED HIGH VOLATILE C BITUMINOUS COAL[1]

Size Fraction (mm)	wt%	Cum. wt %	% Eq. H_2O	Ash %	V.M. %	F.C.* %	C.V. cal/g	C %	H %	N %	S %	O_2* %
+100	0	0	---	---	---	---	---	---	---	---	---	---
100 x 25.0	2.2	2.2	11.1	16.0	34.4	49.6	6120	63.8	4.7	1.5	0.2	13.8
25.0 x 19.0	3.1	5.3	11.9	15.3	34.2	50.5	6140	64.0	4.5	1.5	0.5	14.2
19.0 x 12.5	7.9	13.2	12.6	14.1	35.7	50.2	6340	65.5	4.6	1.9	0.4	13.5
12.5 x 6.7	24.3	37.5	13.3	15.8	35.2	49.0	6440	65.0	4.3	1.6	0.4	12.9
6.7 x 4.75	14.1	51.6	14.8	12.0	34.4	53.6	6510	68.7	4.8	2.1	0.6	11.8
4.75 x 2.36	20.5	72.1	15.4	13.1	33.7	53.2	6460	65.7	4.3	0.1	0.3	16.5
2/36 x 1.18	13.7	85.8	17.2	13.5	33.1	53.4	6330	66.2	4.2	1.8	0.6	13.7
-1.18	14.2	100.0	19.3	15.6	31.5	52.9	6110	64.6	3.5	1.4	0.4	14.5

[1]All analyses reported on dry basis

*By difference

Table 2

HIGHVALE SUBBITUMINOUS B COAL[1]

Size Fraction (mm)	wt%	Cum. wt %	% Eq. H_2O	Ash %	V.M. %	F.C.* %	C.V. cal/g	C %	H %	N %	S %	O_2* %
+100	0	0	---	---	---	---	---	---	---	---	---	---
100 x 25.0	69.8	69.8	16.0	18.3	30.6	51.1	5630	60.5	3.6	0.8	0.1	16.7
25.0 x 19.0	15.4	85.2	16.1	12.3	31.2	56.5	5780	65.1	3.4	1.0	0.2	18.0
19.0 x 12.5	7.2	92.4	12.0	16.0	31.7	52.3	5840	62.4	3.8	0.8	0.1	16.9
12.5 x 6.7	3.7	96.1	17.6	17.4	30.4	52.2	5540	60.5	3.3	0.5	0.2	18.1
6.7 x 4.75	1.1	97.2	18.1	18.1	30.4	51.5	5400	59.8	3.6	0.9	0.1	17.5
4.75 x 2.36	1.5	98.7	19.2	17.7	29.9	52.4	5490	60.5	3.7	0.2	0.1	17.8
2.36 x 1.18	0.6	99.3	20.9	16.6	30.8	52.6	5530	62.3	3.5	0.9	0.3	16.4
-1.18	0.7	100.0	23.9	21.5	29.1	49.4	5210	57.4	2.8	1.5	0.3	16.5

[1]All analyses on dry basis

*By difference

Table 3

POPLAR RIVER LIGNITE[1]

Size Fraction (mm)	wt%	Cum. wt %	% Eq. H_2O	Ash %	V.M. %	F.C.* %	C.V. cal/g	C %	H %	N %	S %	O_2* %
+100	26.9	26.9	---	10.7	---	---	---	63.9	2.6	0.8	0.4	21.6
100 x 25.0	58.9	85.8	28.2	11.7	34.7	53.6	5630	62.5	3.6	3.6	0.7	17.9
25.0 x 19.0	2.1	87.9	31.3	16.4	35.2	48.4	5600	57.5	3.4	0.7	0.4	21.6
19.0 x 12.5	3.1	91.0	32.8	18.7	34.2	47.1	5370	56.4	3.7	0.8	0.6	19.8
12.5 x 6.7	3.7	94.7	35.9	19.9	32.3	47.8	5040	54.3	2.7	0.7	0.7	21.7
6.7 x 4.75	1.0	95.7	35.9	20.4	31.5	48.1	4680	54.9	3.4	0.8	0.8	19.7
4.75 x 2.36	1.6	97.3	36.1	26.2	30.1	43.7	4390	50.9	2.8	0.7	0.8	18.6
2.36 x 1.18	0.9	98.2	37.9	34.0	28.4	37.6	4010	47.3	2.5	0.6	0.4	15.2
-1.18	1.8	100.0	38.1	33.3	27.9	38.8	4180	46.8	2.6	0.5	0.8	16.0

[1]All analyses on dry basis

*By difference

Table 4

OBED HIGH VOLATILE C BITUMINOUS COAL:
-12.5 mm Process Feed

Equilibrium Moisture, %	:	12.1
Total Moisture, %	:	10.4
Ash, % db	:	13.0
Calorific Value, cal/g db	:	6500
Hardgrove Grindability	:	42

Size Analysis:	Size Fraction (mm)	wt%	Cum. wt%
	12.5 x 6.7	15.9	15.9
	6.7 x 4.75	14.0	29.9
	4.75 x 2.36	26.9	56.8
	2.36 x 1.18	20.3	77.1
	1.18 x 0.6	10.3	87.4
	0.6 x 0.3	3.2	95.9
	-0.15	4.1	100.0

Table 5

HIGHVALE SUBBITUMINOUS B COAL:
-12.5 mm Process Feed

Equilibrium Moisture, %	:	18.4
Total Moisture, %	:	14.0
Ash, % db	:	14.3
Calorific Value, cal/g db	:	5870
Hardgrove Grindability	:	64

Size Distribution:	Size Fraction (mm)	wt%	Cum. wt%
	12.5 x 6.7	38.0	38.0
	6.7 x 4.75	15.5	53.5
	4.75 x 2.36	22.8	76.3
	2.36 x 1.18	12.1	88.4
	1.18 x 0.6	5.7	94.1
	0.6 x 0.3	2.9	97.0
	0.3 x 0.15	1.5	98.5
	-0.15	1.5	100.0

Table 6

POPLAR RIVER LIGNITE
-12.5 mm Process Feed

Equilibrium Moisture, %	:	30.5
Total Moisture, %	:	22.6
Ash, % db	:	12.3
Calorific Value, cal/g db	:	5670
Hardgrove Grindability	:	55

Size Distribution:	Size Fraction (mm)	wt%	Cum. wt%
	12.5 x 6.7	51.6	51.6
	6.7 x 4.75	14.2	65.8
	4.75 x 2.36	16.3	82.1
	2.36 x 1.18	7.8	89.9
	1.18 x 0.6	4.2	94.1
	0.6 x 0.3	2.1	96.2
	0.3 x 0.15	1.2	97.4
	-0.15	2.6	100.0

Table 7

ANALYSIS OF RESIDUA USED FOR COAL BENEFICIATION

RESIDUUM	CLARKSON PDA	CENEX PDA	KOCH 85/100 ASPHALT	EFV BOTTOMS AT 545°C EX DRB	PEACE RIVER D85-70	SUNCOR D84-96	CANMET DEMO PITCH D86-115	COAL TAR
H_2O%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH%	0.0	0.0	0.0	0.0	0.0	1.0	1.9	0.0
C%	86.5	83.8	86.3	87.0	81.2	81.3	86.3	91.5
H%	10.2	9.6	10.4	9.3	9.5	9.8	7.3	5.1
N%	0.6	0.7	0.8	0.8	0.8	0.6	1.3	1.2
S%	1.9	4.5	2.0	1.7	7.5	6.1	3.0	0.4
O% (By Difference)	0.8	1.4	0.5	1.2	1.0	2.2	2.1	2.8
Calorific Value (Cal/gm)	10,060	9,820	10,160	9,930	9,690	9,720	9,290	8,940
Ni (ppm)	31.6	75.0	51.5	32.2	109.0	124.5	151.4	1.2
V (ppm)	57.0	200.0	67.5	54.5	309.0	336.3	365.3	0.4
Softening pt (°C)	64	61	47	119	68.5	67.5	115	---
Penetration (at 25°C)	6	16	77	5	7	7.5	1	---
Density (g/ml at 15.6°C)	1.01	1.05	1.02	1.04	1.06	1.06	1.13	1.21
Viscosity (cps) at 150°C at 200°C	436 60	577 77	114 25	1,055 95	667 90	687 96	2,930 118	6.0

Table 8

RESULTS FROM BATCH IMMERSION EXPERIMENTS

Coal Type	Coal Size (Fine) (Coarse)	Residuum Temp. (°C)	Temp. Drop °C/100g of sample	Product Analyses Equilibrium Moisture (%)	Total Moisture (%)	Residuum Content (%)
Obed	F	200	2.0	3.3	4.0	10.9
High Volatile	C	200	1.5	0.8	2.5	6.5
C	F	300	3.2	3.0	0.9	7.6
Bituminous	F	300	3.3	2.4	1.0	7.6
	C	300	2.4	0.8	0.2	5.1
	C	300	---	0.8	0.4	4.9
Highvale	F	200	2.4	15.5	2.3	12.8
Subbituminous	F	200	2.4	16.2	3.0	13.5
B	C	200	1.6	9.0	1.9	6.7
	F	300	2.9	6.7	1.9	14.9
	C	300	4.0	7.6	0.7	9.1
	C	300	3.2	8.2	0.5	9.2
Poplar River	F	200	4.2	11.0	4.6	24.3
Lignite	F	200	3.2	8.1	5.0	30.2
	C	200	2.5	9.7	3.7	19.7
	C	200	2.6	10.4	4.1	25.0
	F	300	4.2	10.2	4.4	19.4
	C	300	---	11.2	1.3	22.2

Table 9

EXPERIMENTAL PROGRAM TO EVALUATE THE INJECTION METHOD

TEST SERIES	PURPOSE/EFFECTS EVALUATED			OUTCOME
1.	**Preliminary Screening Tests using Obed and CENEX**			**SELECT**
	1. Product Temperature	:	200°C, 300°C	Temp.
	2. Residuum Application Rate	:	2%, 4%	% Res.
	3. Residence Time	:	6 min, 12 min	
	4. Pre-drying to Mixing Ratio	:	1:1, 4:1	
	5. Particle Size	:	12.5 x 0mm, 12.5 x 1.7mm	
	6. Drying Gas Oxygen Content	:	<5%, >15%	% O_2
2.	**Confirmation Tests using Obed and Clarkson**			**SELECT**
	1. Product Temperature	:	200°C, 300°C	Temp.
	2. Residuum Application Rate	:	2%, 4%	% Res.
	3. Drying Gas Oxygen Content	:	<5%, >15%	
3.	**Effect of Residuum Type using Obed and 4% Application Rate**			**SELECT**
	. Eight Different Residua	1.	Cenex (C)	C
		2.	Clarkson (CL)	CL
		3.	Koch	
		4.	EFV Bottoms	
		5.	Suncor	
		6.	Peace River (PR)	PR
		7.	CANMET Demo (CD)	CD
		8.	Coal Tar	
	. Product Temperature	:	200°C, 300°C	
4.	**Confirmation of Significant Variables Using Lower Rank Coals**			
	. Coal Rank	:	Highvale, Poplar	
	. Product Temperature	:	200°C, 300°C	
	. Residuum Application Rate	:	2%, 4%	
	. Residuum Type	:	Cenex, Clarkson, Peace River, CANMET Demo	
5.	**Optimum Conditions**			
	. Coal Rank	:	Obed, Highvale, Poplar River	
	. Residuum Type	:	Clarkson	
	. Product Temperature	:	300°C	
	. Residuum Application Rate	:	4%	

Table 10

PRELIMINARY SCREENING TESTS OF PROCESS VARIABLES USING OBED COAL AND CENEX PDA

Test #	Test Conditions						Product Qualities		
	Residuum Application Rate wt%	Coal Temperature °C	Residence Time min	Pre-Drying to Mixing Ratio	Coal Particle Size mm	Drying Gas O_2 Content %	Eq. Moisture %	Total Moisture %	Residuum Determined %
1	2	200	12	1:1	12.5 x 0	>15	11.4	0.8	1.3
2	4	200	12	1:1	12.5 x 0	>15	10.6	1.6	2.2
3	4	200	12	1:1	12.5 x 0	>15	11.0	1.5	3.9
4	4	200	6	1:1	12.5 x 0	>15	10.9	1.8	3.5
5	4	200	12	4:1	12.5 x 0	>15	11.4	1.1	4.7
6	4	200	12	1:1	12.5 x 1.7	>15	11.1	1.6	2.3
7	4	300	12	1:1	12.5 x 0	>15	8.8	0.6	1.0
8	4	300	12	1:1	12.5 x 0	<5	7.0	0.5	3.4

Table 11

TESTS DONE TO CONFIRM THE SIGNIFICANT VARIABLES ESTABLISHED FROM PRELIMINARY SCREENING TESTS: OBED COAL AND CLARKSON PDA

Test #	Test Conditions[1]			Product Qualities		
	Coal Temperature °C	Residuum Application Rate wt%	Drying Gas O_2 Content %	Eq. Moisture %	Total Moisture %	Residuum Determined %
1	200	2	>15	10.7	0.8	1.7
2	200	4	>15	11.9	1.7	3.6
3	200	4	>15	9.9	0.8	3.8
4	300	2	>15	8.8	0.7	0.5
5	300	2	<5	6.8	0.7	1.7
6	300	4	>15	6.5	0.6	0.8
7	300	4	<5	8.5	0.8	1.6

[1]For all tests: Pre-drying to mixing ratio was 1:1, residence time was 12 min, particle size was 12.5 x 0 mm

Table 12

SCREENING TEST RESULTS: EVALUATION OF RESIDUUM TYPE

Residuum	Target Product Temp. °C	Product Analyses		
		Eq. Moisture %	% Residuum Determined	% Moisture
CENEX	200	10.6	2.2	1.6
	200	11.0	3.9	1.5
	300	8.8	1.0	0.6
CLARKSON	200	11.9	3.6	1.7
	200	9.9	3.8	0.8
	300	6.5	0.8	0.6
SUNCOR	200	11.0	3.0	1.1
	200	11.0	3.7	1.1
	300	8.0	0.5	0.9
PEACE RIVER	200	11.1	2.4	1.1
	200	11.3	2.4	1.2
	300	6.9	0.5	0.6
CANMET DEMO	200	11.3	3.6	1.4
	200	11.0	3.5	1.1
	300	9.0	0.6	0.9
EFV BOTTOMS	200	10.4	3.7	1.0
	200	10.7	4.4	1.2
	300	8.1	0.9	0.8
COAL TAR	200	11.2	1.5	1.4
	200	11.3	2.1	1.1
	300	8.5	0.3	0.9
KOCH 85/100	200	11.0	3.9	0.8
	200	11.0	3.5	0.9
	300	9.3	2.0	0.3

Table 13

TEST RESULTS USING HIGHVALE AND POPLAR RIVER WITH THE FOUR RESIDUA SELECTED USING OBED COAL

Test Conditions[1]			Product Qualities					
			Highvale			Poplar River		
Residuum Type	Appl. Rate wt%	Coal Temperature °C	Eq. Moisture %	Total Moisture %	Residuum Determined %	Eq. Moisture %	Total Moisture %	Residuum Determined %
CENEX	2	200	19.5	1.3	0.1	24.2	3.1	3.7
CENEX	2	300	16.1	0.6	0.1	19.5	2.2	1.8
CENEX	4	200	17.4	0.7	2.6	27.1	2.9	7.2
CENEX	4	300	15.1	0.4	0.8	20.3	2.0	5.8
CLARKSON	2	200	17.6	7.0	1.0	27.0	1.1	2.3
CLARKSON	2	300	15.5	1.4	0.1	18.6	0.7	0.8
CLARKSON	4	200	16.8	2.0	2.7	27.2	1.7	5.2
CLARKSON	4	300	14.7	0.1	2.7	19.2	0.7	2.6
PEACE R.	2	200	18.1	0.7	1.6	25.0	1.5	3.7
PEACE R.	2	300	14.3	0.2	0.5	19.1	0.5	2.3
PEACE R.	4	200	17.9	0.8	3.0	25.6	1.2	6.4
PEACE R.	4	300	14.3	0.1	0.9	18.6	0.5	3.2
CANMET D.	2	200	18.3	0.7	3.5	28.7	2.1	2.5
CANMET D.	2	300	16.2	0.4	0.1	19.6	1.8	1.7
CANMET D.	4	200	16.8	0.6	5.5	23.7	1.8	3.1
CANMET D.	4	300	15.4	0.3	1.1	19.6	1.3	1.9

[1]For all Tests: residence time = 12 min, pre-drying to mixing ratio = 1:1, particle size = 12.5 x 0 mm, drying gas oxygen content >15%

Table 14

INTERACTION BETWEEN TEMPERATURE AND RESIDUUM TYPE

Temp. °C	Coal	Equilibrium Moisture, % Clarkson PDA	Peace River	Cenex PDA	CANMET DEMO
200	Obed	10.9	11.2	10.8	11.2
200	Highvale	17.2	18.0	18.4	17.5
200	Poplar River	27.1	25.3	23.2	26.3
Average		18.4	18.2	17.5	18.3
300	Obed	6.5	6.9	8.8	9.0
300	Highvale	15.1	14.3	15.6	15.8
300	Poplar River	18.9	18.9	19.9	19.6
Average		13.5	13.4	14.8	14.8

*200°C Obed results are for duplicate tests (4% applied residuum). 300°C Obed results are single values (one test only, not average of two). 200°C and 300°C Highvale and Poplar River results are averages of two tests done at different residuum application rates (2% and 4%). Individual results can be found in Tables 12 and 13.

Table 15

EFFECT OF TEMPERATURE ON EQUILIBRIUM MOISTURE:
NO RESIDUUM APPLIED

Coal Temperature °C	Equilibrium Moisture		
	Obed	Highvale	Poplar River
20	12.1	18.4	30.5
200	11.6	17.8	30.6
300	9.5	15.3	19.7

Table 16

EFFECT OF RESIDUUM APPLICATION RATE ON PRODUCT EQUILIBRIUM MOISTURE

Residuum	Application Rate* %	Highvale	Poplar River
CLARKSON	2	16.6	22.8
	4	15.7	23.2
PEACE RIVER	2	16.2	22.1
	4	16.1	22.1
CENEX	2	17.8	21.8
	4	16.3	21.2
CANMET DEMO	2	17.2	24.2
	4	16.0	21.8
Average	2	16.9	22.7
	4	16.0	22.1

*2% results are average of 200°C and 300°C tests, as are 4% results.

Table 17

EQUILIBRIUM MOISTURE REDUCTIONS ACHIEVED FOR THE THREE COAL RANKS

Process Condition	% Reduction in Equilibrium Moisture[1]					
	Obed hvCb		Highvale sub B		Poplar River lignite	
	min.	max.	min.	max.	min.	max.
200°C	2	18	1	10	6	28
300°C	19	46	12	22	33	39

[1]Untreated Equilibrium Moisture values: Obed = 12.1%; Highvale = 18.4%; Poplar River = 30.5%

Table 18

RESULTS FOR TESTS DONE AT OPTIMUM PROCESSING CONDITIONS[1]

Coal Feedstock	Product Qualities		
	Equilibrium Moisture %	Total Moisture %	Residuum Determined %
Obed	8.9	0.0	1.6
Highvale	15.0	0.6	2.0
Poplar River	19.8	0.8	3.6

[1]For each test, conditions were:

- 300°C product temperature
- Clarkson PDA applied at 4wt%
- 12 min residence time
- 1:1 pre-drying to mixing ratio
- 12.5 x 0 mm particle size range
- drying gas O_2 content >15%

Table 19

CALORIFIC VALUE ENHANCEMENT

Sample	Calorific Values, cal/g		
	Dry, Ash-Free	Moist, Ash-Free	*Moist Ash-In
Poplar River Feed	6470	5210	4570
Poplar River Product	6730	5910	5160
Highvale Feed	6850	5880	5040
Highvale Product	6940	6270	5160
Obed Feed	7470	6770	5890
Obed Product	7540	7130	6020

*Calorific values of feeds and products if at equilibrium with a 21°C and 75% relative humidity atmosphere.

Table 20

MOISTURE SORPTION TEST RESULTS[1]

Coal Sample[2]	Initial Moisture %	Moisture Sorption Cum. Weight Gain (+) or Loss (-) After 24 hrs	48 hrs	72hrs
Obed Feed	10.5	-1.1	-1.2	-1.2
Obed Product	0.0	+3.7	+5.1	+5.7
Highvale Feed	14.0	+0.2	+0.2	+0.2
Highvale Product	0.6	+7.5	+9.4	+10.1
Poplar River Feed	24.0	-4.3	-5.3	-5.6
Poplar River Product	0.8	+9.8	+12.0	+12.9

[1]Sorption done in 75% relative humidity, 21°C atmosphere.

[2]Product samples are from Optimum Conditions Tests, Table 18.

Table 21

RESULTS OF OPTIMUM CONDITIONS TESTS: STABILITY EVALUATIONS

Test #	Sample and Test Conditions	O_2 Sorption ml/100g	CO Production ppm	Eq Moisture %	Total Moisture %	Residuum Determined %
1	Obed Feed	24	220	12.1	10.5	---
2	Obed Product, 300°C, 4% PDA	46	1,100	8.9	0.1	1.6
3	Highvale Feed	28	390	18.4	14.0	---
4	Highvale Product, 300°C, 4% PDA	53	1,200	15.0	0.6	1.9
5	Poplar River Feed	83	320	28.7	24.0	---
6	Poplar River Product, 300°C, 4% PDA	39	1,760	19.8	0.8	3.6

Table 22

DUSTINESS TESTS RESULTS:
FEEDS VS. OPTIMUM PRODUCTS

Sample	Test #	Dustiness Index	
		Coarse	Fine
Obed Feed	1	119	2.1
	2	91	0.9
	Average	105	1.5
Obed Product	1	5.5	0
	2	3.5	0
	Average	4.5	0
Highvale Feed	1	215	15
	2	277	19
	Average	246	17
Highvale Product	1	18	0
	2	8.6	0
	Average	13	0
Poplar R. Feed	1	264	20
	2	250	24
	Average	257	22
Poplar R. Product	1	110	0.6
	2	88	0.6
	Average	99	0.6

Table 23

SIZE DISTRIBUTIONS OF FEED COALS AND PRODUCTS FROM OPTIMUM CONDITIONS TESTS

Size Fraction mm	FEED					
	Obed		Highvale		Poplar River	
	Wt%	Cum Wt%	Wt%	Cum Wt%	Wt%	Cum Wt%
+6.7	15.9	15.9	38.0	38.0	51.6	51.6
6.7 x 4.75	14.0	29.9	15.5	53.5	14.2	65.8
4.75 x 2.36	26.9	56.8	22.8	76.3	16.3	82.1
2.36 x 1.18	20.3	77.1	12.1	88.4	7.8	89.9
1.18 x 0.6	10.3	87.4	5.7	94.1	4.2	94.1
0.6 x 0.3	5.3	92.7	2.9	97.0	2.1	96.2
0.3 x 0.15	3.2	95.9	1.5	98.5	1.2	97.4
-0.15	4.1	100.0	1.5	100.0	2.6	100.0
	PRODUCT					
+6.7	17.0	17.0	25.6	25.6	24.0	24.0
6.7 x 4.75	16.6	33.6	18.0	43.6	17.0	41.0
4.75 x 2.36	28.6	62.2	28.7	72.3	25.7	66.7
2.36 x 1.18	20.0	82.2	15.9	88.2	14.8	81.5
1.18 x 0.6	10.9	93.1	7.4	95.6	8.1	89.6
0.6 x 0.3	5.0	98.1	2.8	98.4	5.6	95.2
0.3 x 0.15	1.3	99.4	0.9	99.3	2.7	97.9
-0.15	0.6	100.0	0.7	100.0	2.1	100.0

Table 24

FLOWABILITY TEST RESULTS FOR FEED COALS AND PRODUCTS FROM OPTIMUM CONDITIONS TESTS

Sample	Test #	Durham Cone Index[1] Feed	Product
Obed	1	2.9	3.3
	2	3.0	3.4
	Average	2.9	3.3
Highvale	1	3.4	3.1
	2	3.6	3.1
	Average	3.5	3.1
Poplar River	1	3.9	3.8
	2	4.0	3.9
	Average	3.9	3.8

[1]The lower the index the better the flow

Table 25

RESULTS OF STABILITY EVALUATIONS FOR SELECTED TESTS

Test #	Sample and Test Conditions	O_2 Sorption ml/100g	CO Production ppm	Eq H_2O %	Total H_2O %	Residuum Determined %
1	Poplar River Feed	83	320	28.7	24.0	---
2	Poplar River Product, 300°C, 4% PDA	39	1,760	19.8	0.8	3.6
3	Highvale Feed	28	390	18.4	14.0	---
4	Highvale Product, 300°C, 4% PDA	53	1,200	15.0	0.6	1.9
5	Obed Feed	24	220	12.1	10.5	---
6	Obed Product, 300°C, 0% Residuum	99	2,170	9.5	0.7	---
7	Obed Product, 300°C, 4% PDA	46	1,100	8.9	0.1	1.6
8	Obed Product, 300°C, 4% PDA, <5% O_2	41	670	8.5	0.5	3.0
9	Obed Product, 300°C, 4% PDA, H_2O cooled	71	20	9.5	17.7	3.1
10	Obed Product, 300°C, 4% Koch 85/100	56	1,000	9.5	0.3	2.5
11	Obed Product, 300°C, 8% Koch 85/100 Emulsion, <5% O_2	160	1,300	7.9	0.4	1.9
12	Obed Product, 300°C, air-cooled then 8% Koch 85/100 Emulsion at room temperature	64	1,020	9.6	2.2	3.1

Table 26

EVALUATION OF EFFECT OF EMULSION

Test #	Type[1]	Rate %	Coal Temp. °C	Eq. Moisture %	Total Moisture %	Residuum Determined %
Preliminary Tests						
1	Neat	4	200	11.0	0.8	3.9
2	Neat	4	200	11.0	0.9	3.5
3	Neat	4	300	9.3	0.3	2.0
4	Emulsion	8	200	10.5	1.0	3.8
5	Emulsion	8	200	10.9	1.1	4.3
6	Emulsion	8	300	8.6	1.1	1.1
Confirmation Tests						
7	Neat	4	200	10.5	0.5	3.6
8	Neat	4	200	10.8	0.6	4.1
9	Neat	4	300	9.5	0.4	2.2
10	Neat	4	300	9.5	0.4	2.0
11	Emulsion	8	200	11.7	0.5	2.5
12	Emulsion	8	200	11.8	0.6	2.1
13	Emulsion	8	300	9.9	0.4	1.5
14	Emulsion	8	300	9.7	0.4	1.2

[1]Neat = neat Koch 85/100 asphalt; Emulsion = 55% Koch 85/100: 45% water

Table 27

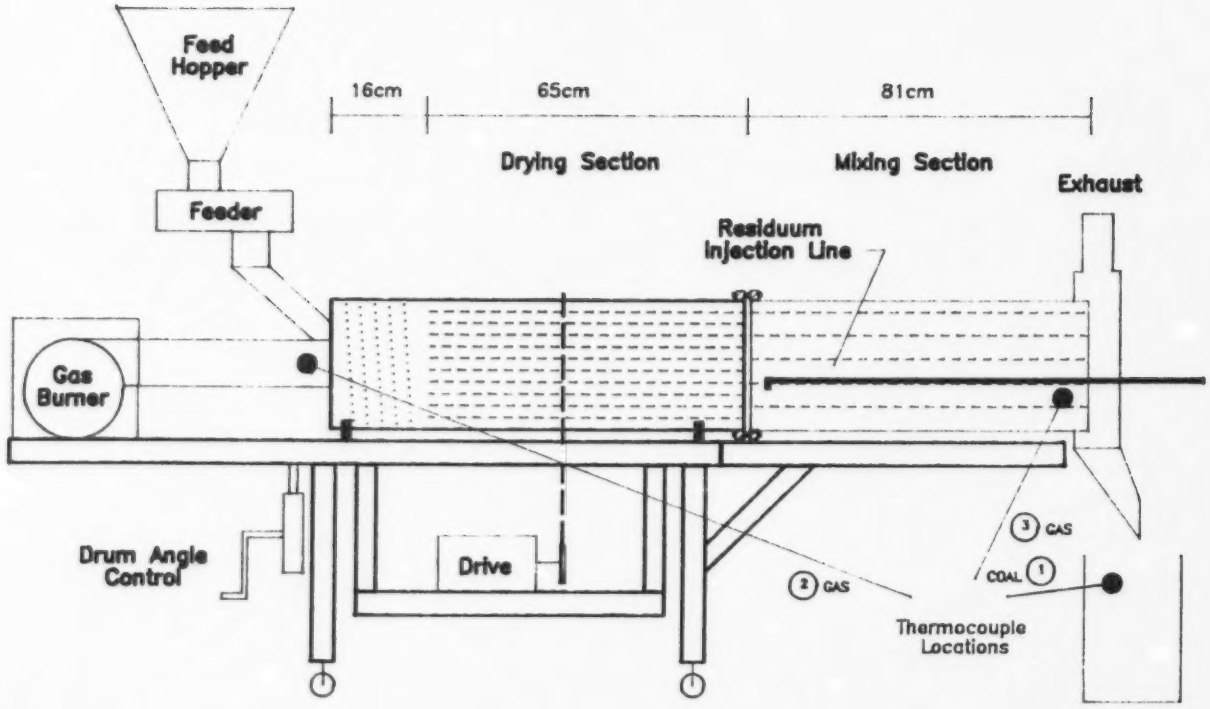
TESTS EVALUATING PROCESSING OPTIONS AVAILABLE WITH EMULSION

Test #	Test Conditions[1]	Product Quality		
		Eq. Moisture %	Total Moisture %	Residuum Determined %
1	Neat, 4% Rate, 300°C, Drying Gas <5% O_2	9.5	0.3	2.5
2	Neat, 4% Rate, 300°C, Drying Gas <5% O_2	9.7	0.4	1.6
3	Emulsion, 8% Rate, 300°C, Drying Gas <5% O_2	7.9	0.4	1.9
4	Emulsion, 8% Rate, 300°C, Drying Gas <5% O_2	7.7	0.3	1.9
5	0% at 300°C, cool, Neat, 4% Rate, 200°C, Drying Gas <5% O_2	8.4	0.1	3.6
6	0% at 300°C, cool, Neat, 4% Rate, 200°C, Drying Gas <5% O_2	8.3	0.1	3.6
7	0% at 300°C, cool, Emulsion, 8% Rate, 20°C	9.3	2.7	5.0
8	0% at 300°C, cool, Emulsion, 8% Rate, 20°C	9.6	2.2	3.1
9	0% at 300°C, cool, Emulsion, 8% Rate, 200°C	9.7	0.3	2.2

[1]Neat = neat Koch 85/100 asphalt; Emulsion = 55% Koch 85/100: 45% water

FIGURE 1

CONTINUOUS UNIT



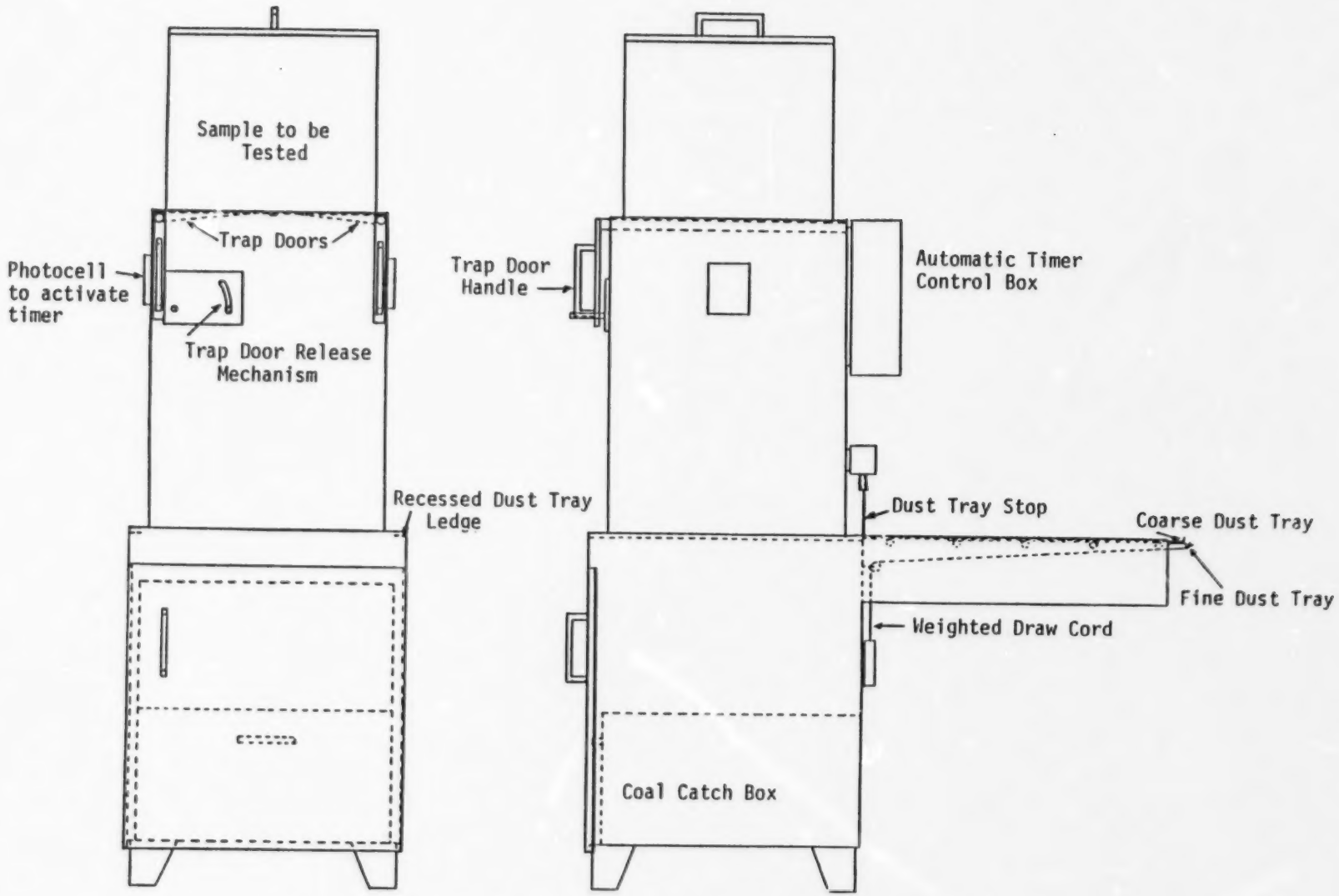


FIGURE 2: CMRC's Modified ASTM Dustiness Cabinet

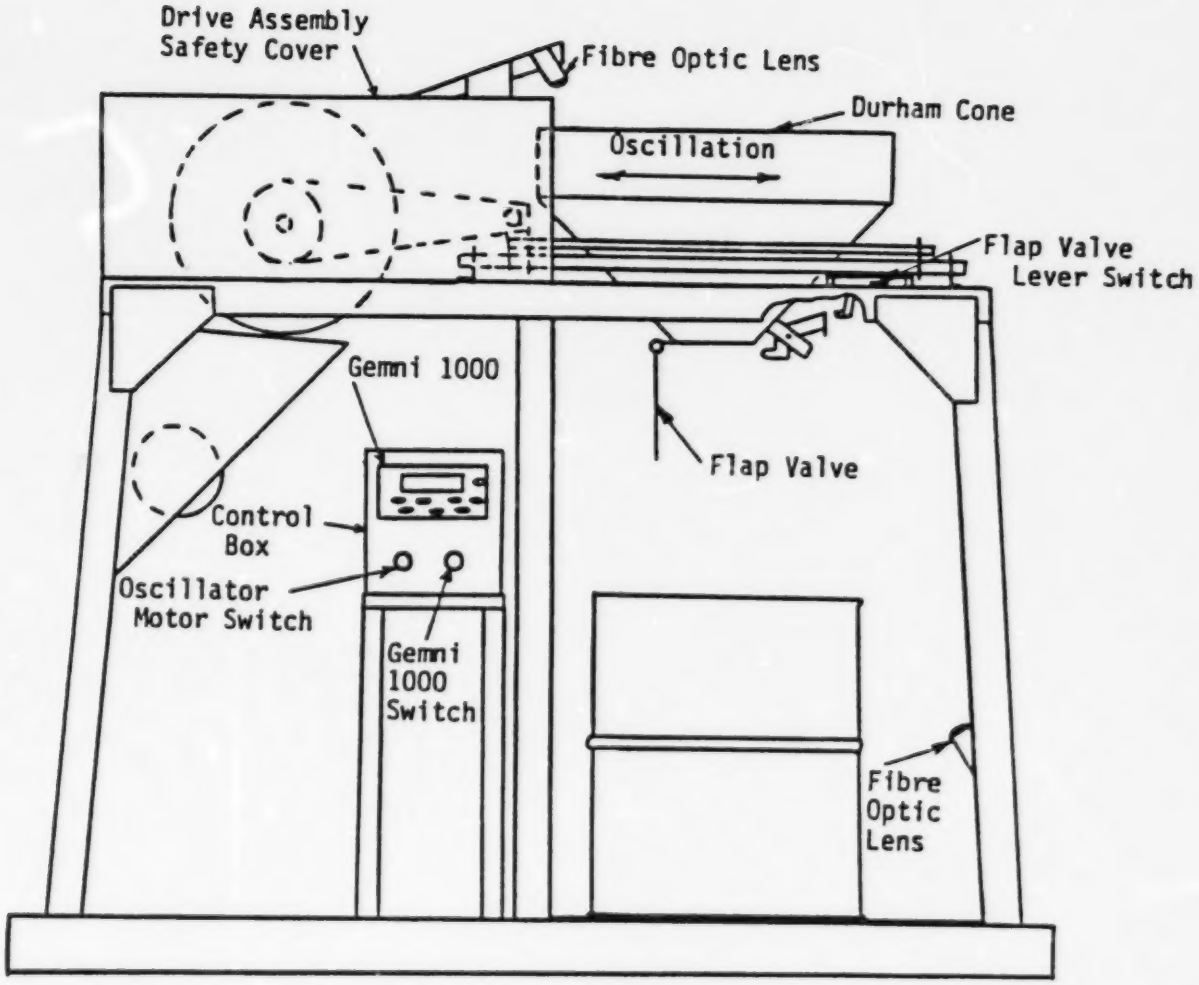


Figure 3: Durham Cone Apparatus for Evaluating Coal Flowability

Figure 4

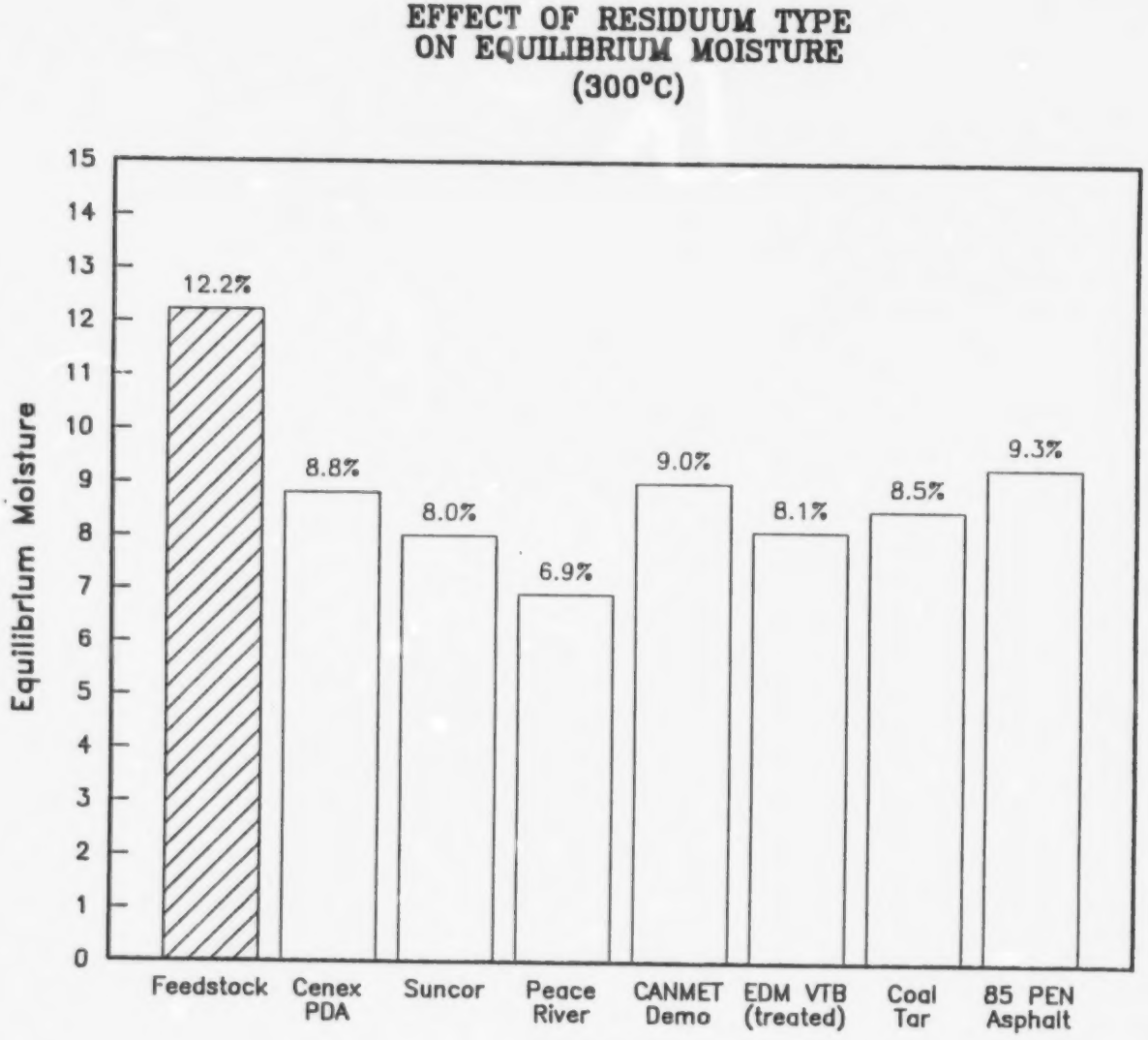

EFFECT OF RESIDUUM TYPE
ON EQUILIBRIUM MOISTURE
(300°C)
Equilibrium Moisture
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
12.2%
8.8%
8.0%
6.9%
9.0%
8.1%
8.5%
9.3%
Feedstock
Cenex PDA
Suncor
Peace River
CANMET Demo
EDM VTB (treated)
Coal Tar
85 PEN Asphalt

Figure 5

EFFECT OF TEMPERATURE ON EQUILIBRIUM MOISTURE FOR LOW RANK COAL

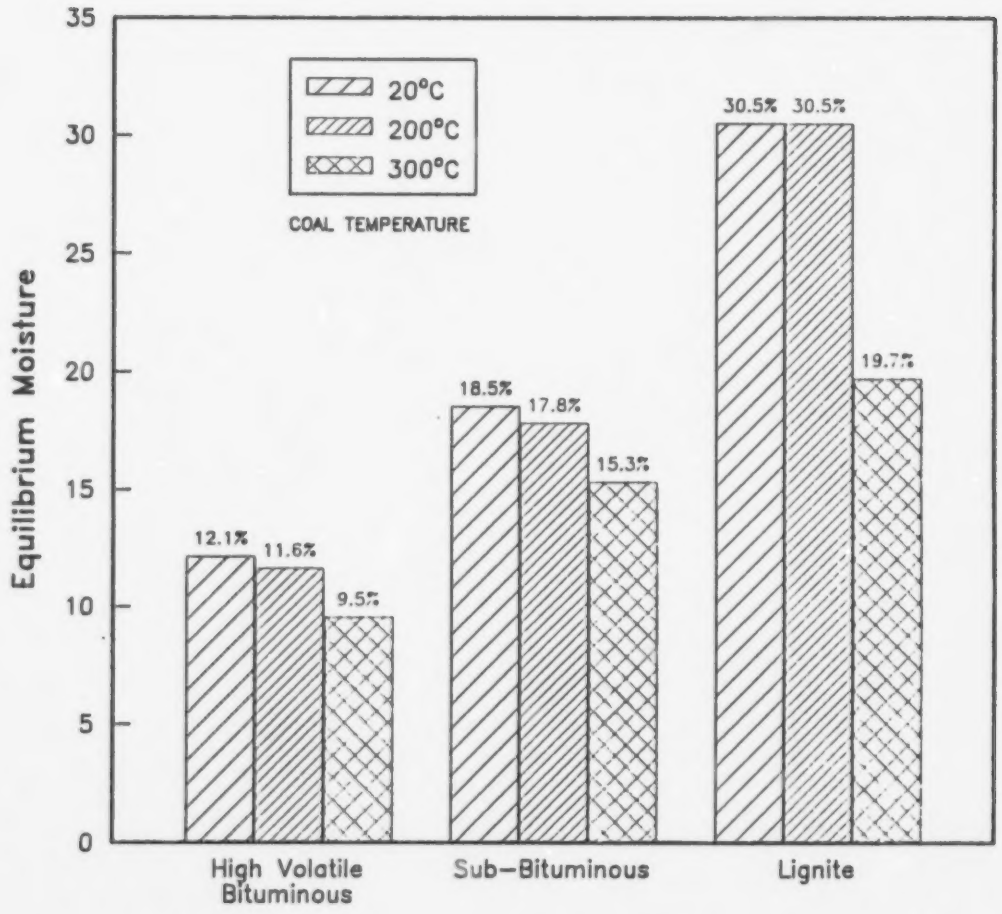


Figure 6

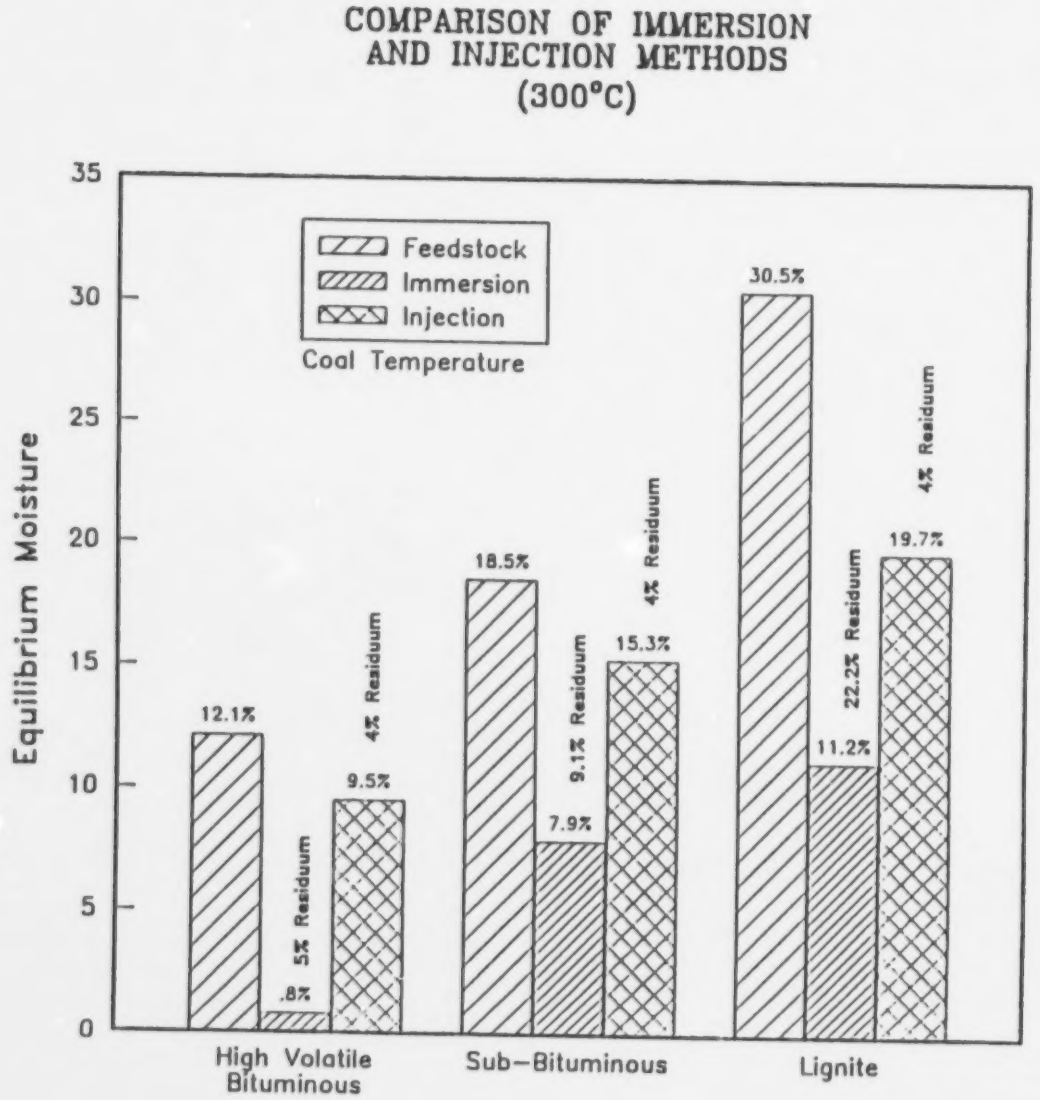

COMPARISON OF IMMERSION
AND INJECTION METHODS
(300°C)
Equilibrium Moisture
35
30
25
20
15
10
5
0
Feedstock
Immersion
Injection
Coal Temperature
12.1%
.8%
5% Residuum
9.5%
4% Residuum
18.5%
7.9%
9.1% Residuum
15.3%
4% Residuum
30.5%
11.2%
22.2% Residuum
19.7%
4% Residuum
High Volatile
Bituminous
Sub-Bituminous
Lignite

FIGURE 7

TWO–STAGE PROCESS SCHEME

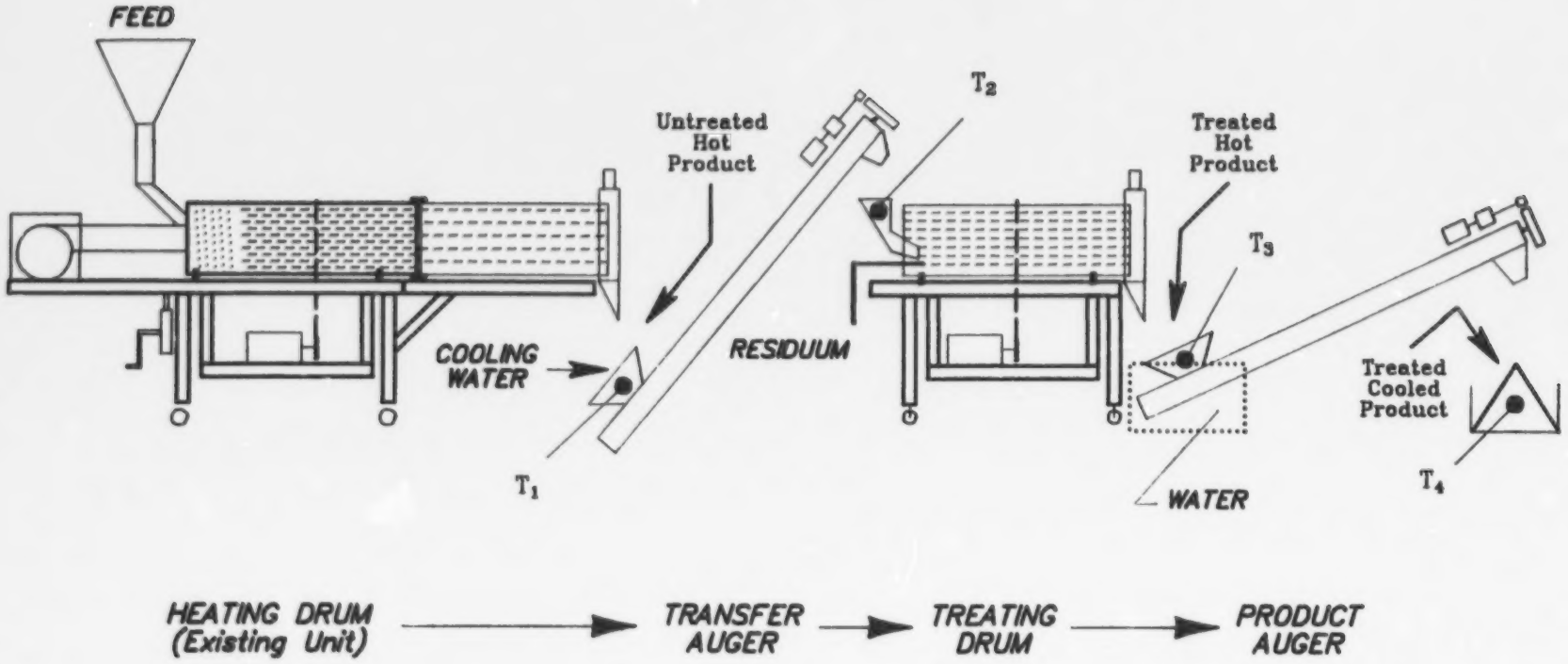
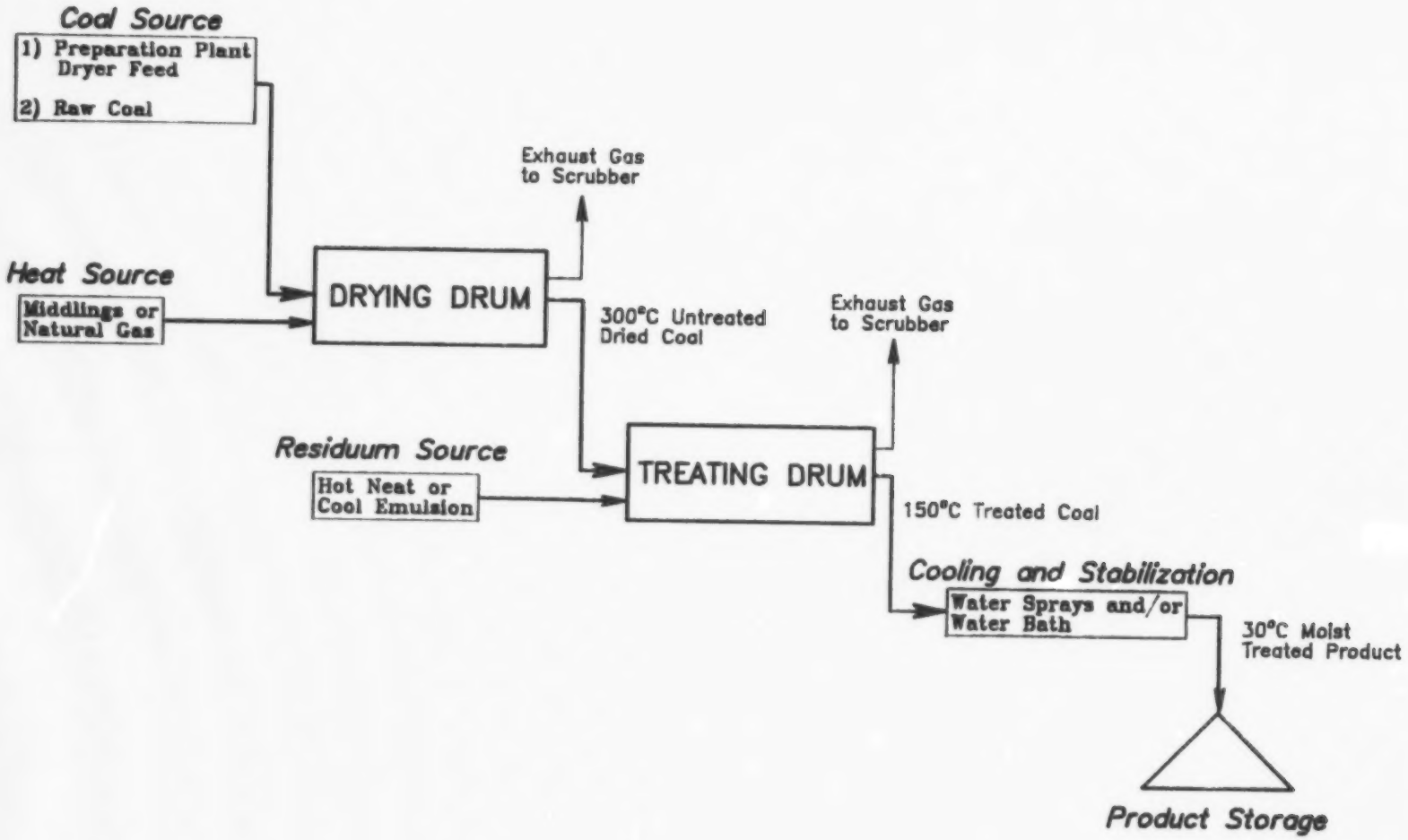


FIGURE 8

FLOWSHEET OF TWO–STAGE PROCESS CONCEPTUAL DESIGN



Durham Cone Test Procedure

The Durham Cone is used to provide comparative data for evaluating the relative flowability of coals. The general test procedure is:

1. Prepare a representative 10 kg test sample.
2. Close flap on cone outlet.
3. Place test sample in cone.
4. Start vibration and allow to vibrate for 10 seconds.
5. After 10 seconds open flap valve and allow coal to flow out of cone. If coal does not flow wait 60 seconds then stop test and record as "no flow," using a value of 60 in computing index.
6. Record time for cone to empty, as indicated by automatic Gemini timer.
7. Repeat procedure a further five times using same test sample.
8. The Durham Cone Index is computed as the average of the last five times. The first time for each sample is not used.
9. Repeat test procedure with a second test sample.

APPENDIX 1

TEST PROCEDURES

Durham Cone

APPENDIX 2

EXPERIMENTAL DATA FOR CONTINUOUS UNIT TESTS

APPENDIX 2
EXPERIMENTAL DATA FOR CONTINUOUS UNIT TESTS

The following table provides the processing conditions and product qua ty analyses for all tests done using the continuous unit injection method. The tests are not listed in the exact order they were performed. The tests are grouped by coal, then the optimum conditions tests, and finally the tests done to evaluate emulsions.

With respect to the following table, the symbols and their meanings are:

1. Coal
   - O = Obed
   - H = Highvale
   - P = Poplar River

2. Residuum
   - CE = Cenex PDA
   - CI = Clarkson PDA
   - SU = Suncor
   - PR = Peace River
   - CD = CANMET Demo
   - VB = Thermally Treated Vacuum Tower Bottoms
   - CT = Coal Tar
   - KO = Koch 85/100
   - KE = Koch 85/100 -55% Emulsion

3. Special Condition : Conditions different from the standard are indicated. Standard conditions were:

- Particle Size = 12.5 mm x 0
- Pre-drying to mixing ratio of 1:1
- Residence time of 12 minutes
- Drying gas oxygen content greater than 15%
- Hot products air-cooled

Table A2-1

Test #	Test Conditions					Product Quality		
	Coal[1]	Residuum[2] Type	Residuum[2] Rate %	Coal Temperature °C	Special Condition[3]	Eq. Moisture %	Total Moisture %	Residuum Determined %
1	O	---	0	200	Untreated	11.64	1.47	---
2	O	---	0	300	Untreated	9.53	0.72	---
3	O	CE	2	200		11.38	0.77	1.33
4	O	CE	4	200		10.64	1.59	2.22
5	O	CE	4	200		11.03	1.46	3.86
6	O	CE	4	200	4:1 Dry.:Mix. Ratio	10.87	1.81	3.53
7	O	CE	4	200	6 min. residence time	11.45	1.09	4.67
8	O	CE	4	200	12.5 x 1.7 mm coal	11.07	1.62	2.33
9	O	CE	4	300		8.83	0.63	1.04
10	O	CE	4	300	Dry. Gas < 5% O_2	7.05	0.47	3.40
11	O	CL	2	200		10.75	0.84	1.73
12	O	CL	4	200		11.90	1.75	3.57
13	O	CL	4	200		9.95	0.85	3.80
14	O	CL	2	300		8.79	0.67	0.48
15	O	CL	2	300	Dry. Gas < 5% O_2	6.81	0.74	1.67
16	O	CL	4	300		6.51	0.74	1.67
17	O	CL	4	300	Dry. Gas < 5% O_2	8.55	0.77	1.61
18	O	SU	4	200		10.96	1.08	3.00
19	O	SU	4	200		10.95	1.06	3.70
20	O	SU	4	300		7.99	0.95	0.47
21	O	PR	4	200		11.12	1.06	2.45
22	O	PR	4	200		11.32	1.22	2.43
23	O	PR	4	300		6.94	0.60	0.47
24	O	CD	4	200		11.33	1.37	3.58
25	O	CD	4	200		11.04	1.10	3.55
26	O	CD	4	300		8.96	0.89	0.58
27	O	VB	4	200		10.42	0.96	3.70
28	O	VB	4	200		10.68	1.25	4.40
29	O	VB	4	300		8.12	0.79	0.86
30	O	CT	4	200		11.24	1.40	1.47
31	O	CT	4	200		11.34	1.15	2.15
32	O	CT	4	300		8.52	0.92	0.34

Test #	Test Conditions					Product Quality		
	Coal[1]	Residuum[2] Type	Rate %	Coal Temperature °C	Special Condition[3]	Eq. Moisture %	Total Moisture %	Residuum Determined %
33	O	KO	4	200		11.01	0.81	3.86
34	O	KO	4	200		11.00	0.89	3.47
35	O	KO	4	300		9.27	0.33	2.02
36	H	---	0	200	Untreated	17.83	1.58	---
37	H	---	0	300	Untreated	15.31	1.40	---
38	H	CE	2	200		19.47	1.26	0.07
39	H	CE	2	300		16.15	0.61	0.09
40	H	CE	4	200		17.44	0.68	2.59
41	H	CE	4	300		15.15	0.37	0.79
42	H	CE	2	300	Dry. Gas <5% O_2	15.50	0.46	1.88
43	H	CE	4	300	Dry. Gas <5% O_2	15.15	0.29	2.36
44	H	CL	2	200		17.63	2.03	1.03
45	H	CL	2	300		15.51	1.43	0.07
46	H	CL	4	200		16.83	1.97	2.69
47	H	CL	4	300		14.66	0.10	2.68
48	H	PR	2	200		18.09	0.72	1.56
49	H	PR	2	300		14.30	0.23	0.52
50	H	PR	4	200		17.87	0.83	3.05
51	H	PR	4	300		14.32	0.15	0.87
52	H	CD	2	200		18.32	0.66	3.47
53	H	CD	2	300		16.18	0.45	0.09
54	H	CD	4	200		16.68	0.60	5.53
55	H	CD	4	300		15.40	0.27	1.13
56	P	---	0	200	Untreated	30.58	2.46	---
57	P	---	0	300	Untreated	19.68	1.01	---
58	P	CE	2	200		24.22	3.07	3.66
59	P	CE	2	300		19.49	2.25	1.78
60	P	CE	4	200		22.10	2.91	7.20
61	P	CE	4	300		20.33	2.02	5.76
62	P	CL	2	200		26.97	1.09	2.28
63	P	CL	2	300		18.59	0.75	0.79
64	P	CL	4	200		27.19	1.70	5.23
65	P	CL	4	300		19.21	0.66	2.61
66	P	PR	2	200		25.00	1.52	3.70
67	P	PR	2	300		19.15	0.50	2.26

Test #	Test Conditions					Product Quality		
	Coal[1]	Residuum[2] Type	Residuum[2] Rate %	Coal Temperature °C	Special Condition[3]	Eq. Moisture %	Total Moisture %	Residuum Determined %
68	P	PR	4	200		25.60	1.19	6.36
69	P	PR	4	300		18.60	0.48	3.21
70	P	CD	2	200		28.74	2.15	2.49
71	P	CD	2	300		19.61	1.28	1.95
72	P	CD	4	200		23.95	1.85	3.14
73	P	CD	4	300		19.65	1.30	1.90
74	O	CL	4	300		8.86	0.04	1.58
75	O	CL	4	300	Dry. Gas < 5% O_2	8.47	0.52	2.97
76	O	CL	4	300	Water Cooled	9.54	17.71	3.06
77	H	CL	4	300		15.00	0.56	1.95
78	H	CL	4	300	Dry. Gas < 5% O_2	15.11	0.99	2.93
79	H	CL	4	300	Water Cooled	16.08	22.49	2.92
80	P	CL	4	300		19.83	0.77	3.65
81	P	CL	4	300	Dry. Gas < 5% O_2	19.65	1.68	4.38
82	P	CL	4	300	Water Cooled	19.70	29.93	4.49
83	O	KO	4	200		10.54	0.47	3.61
84	O	KO	4	200		10.78	0.60	4.07
85	O	KO	4	300	2nd Stage 200°C, Dry. Gas < 5% O_2	8.40	0.09	3.61
86	O	KO	4	300	2nd Stage 200°C, Dry. Gas < 5% O_2	8.31	0.13	3.56
87	O	KO	4	300		9.46	0.40	2.19
88	O	KO	4	300		9.47	0.40	1.99
89	O	KO	4	300	Dry. Gas < 5% O_2	9.47	0.33	2.46
90	O	KO	4	300	Dry. Gas < 5% O_2	9.69	0.40	1.65
91	O	KE	8	200		10.48	1.05	3.84
92	O	KE	8	200		10.91	1.08	4.32
93	O	KE	8	200		11.75	0.46	2.46
94	O	KE	8	200		11.83	0.60	2.07
95	O	KE	8	300		8.60	1.08	1.07
96	O	KE	8	300		9.88	0.40	1.49
97	O	KE	8	300		9.72	0.37	1.25
98	O	KE	8	300	Dry. Gas < 5% O_2	7.89	0.38	1.94
99	O	KE	8	300	Dry. Gas < 5% O_2	7.72	0.30	1.87
100	O	KE	8	300	2nd Stage 20°C	9.29	2.71	5.02
101	O	KE	8	300	2nd Stage 20°C	9.65	2.20	3.09
102	O	KE	8	300	2nd Stage 200°C	9.66	0.26	2.20